OPTIMIZING THE SPACE TRANSPORTATION SYSTEM

THESIS

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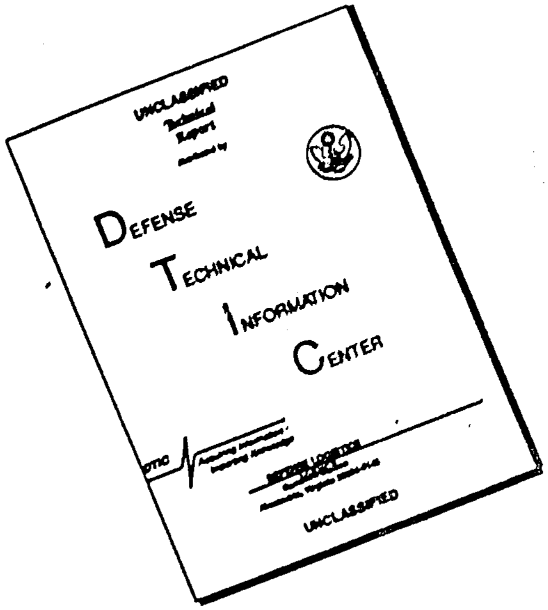

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Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of Master of Science

by

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Graduate Astronautical Engineering

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Preface

Accomplishing this thesis has been both a joy and a nerve shattering experience. Joyful because it illumines such a fascinating portrait of the future, and nerve shattering because of a never ending series of deadlines. Meeting those deadlines would have been impossible without the help of several gracious people. Mr. Vincent Darcy of the NASA provided volumes of information and hours of time explaining the intricacies of Space Shuttle mission planning. Likewise, Mr. Bill Castlen of Rockwell International provided and patiently explained his corporation's Traffic Model for future satellites. Finally, Capt. Aaron DeWispelare kindly consented to serve as my advisor and guided me through some of the darker periods of the past year. Numerous others provided information or words of encouragement and I owe all of them a sincere note of thanks. I would like to dedicate this thesis to these people, and to the men and women of tommorrow's space programs through the prophetic words of one of England's great visionaries, Alfred Lord Tennyson:

> For I dipt into the future, far as human eye
>   could see,
> Saw the Vision of the world, and all the
>   wonder that would be;
> Saw the heavens fill with commerce, argosies
>   of magic sails,
> Pilots of the purple twilight, dropping
>   down with costly bales;

-from Locksley Hall, 1842

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List of Symbols

Acronyms

ABM	- Anti-Ballistic Missile
ASAT	- Anti-Satellite
ET	- External Tank
ETR	- Eastern Test Range
ETS	- External Tank Separation
Hg	- Mercury
LEO	- Low Earth Orbit
MECO	- Main Engine Cut Off
MPS	- Main Propulsion System
NASA	- National Aeronautics and Space Administration
OMS	- Orbital Maneuvering System
OTV	- Orbital Transfer Vehicle
RCS	- Reaction Control System
SOC	- Space Operations Center
SRM	- Solid Rocket Motor
SSME	- Space Shuttle Main Engine
STS	- Space Transportation System
TOF	- Time of Flight
WTR	- Western Test Range

Key Mathematical Characters

A_{sat}	- Satellite Orbit semi-major axis
A_{soc}	- Average deceleration of SOC due to air drag

B	-	Ballistic coefficient
C_d	-	Drag coefficient
e_{sat}	-	Satellite orbit eccentricity
F_{orb}	-	Annual Orbiter launch frequency
F_{sat}	-	Annual satellite launch frequency
g	-	Gravitational acceleration
H	-	Scale height
I	-	Specific impulse
I_{ren}	-	OTV and Shuttle rendezvous orbit inclination
I_{sat}	-	Satellite orbit inclination
I_{soc}	-	SOC orbit inclination
M_c	-	Annual cargo mass transported to SOC
M_{et}	-	ET mass
MF_{asc}	-	OTV fuel mass required to ascend to SOC from Shuttle rendezvous orbit
MF_{dpl}	-	OTV fuel mass required to deploy a satellite from the SOC
MF_{dsc}	-	OTV fuel mass required to descend to the Shuttle rendezvous orbit from the SOC
MF_{msn}	-	$MF_{dpl} + MF_{rtn}$
MF_{oa}	-	Orbiter fuel mass required to ascend to the SOC from MECO
MF_{od}	-	Orbiter fuel mass required to deorbit from the SOC

MF_{rtn} - OTV fuel mass required to return the OTV to the SOC after deploying a satellite

MF_{soc} - Annual fuel mass required for SOC stationkeeping

M_{ft} - Ion thruster fuel tank mass

MM_{etr} - MECO mass for the ETR

MM_{wtr} - MECO mass for the WTR

M_{otv} - OTV mass

M_{pl} - Shuttle payload mass

M_{r} - Shuttle reference mass (see Table 3.1)

M_{sat} - Satellite mass

M_{soc} - SOC mass

M_{sp} - Specific mass (i.e. Number of kg/kw for power system)

M_{str} - Structural mass of ion propelled OTV

M_{thr} - Ion thruster mass

n - Number of satellites in Traffic Model

N - Number of ion thrusters on OTV

NO - Number of ion propelled OTVs based at SOC

P_{wr} - Power required to operate ion thruster

R_{asat} - Radius of satellite orbit at apogee

R_{ren} - OTV and Shuttle rendezvous orbit radius

R_{soc}	-	SOC orbit radius
S	-	Average cross sectional area of SOC
T	-	Thrust of ion thruster
TIM_{avg}	-	Average ion propelled OTV mission duration
TIM_{dpl}	-	Time required to deploy a satellite with an ion propelled OTV
TIM_{rtn}	-	Time required for an ion propelled OTV to return to SOC after deploying a satellite
U	-	Gravitational parameter
ΔV	-	Characteristic velocity
ΔVA_{etr}	-	ETR Orbiter ΔV required to ascend to SOC from MECO
ΔVA_{wtr}	-	WTR Orbiter ΔV required to ascend to SOC from MECO
ΔVD	-	Orbiter ΔV required to deorbit
ΔV_{ren}	-	OTV ΔV required to rendezvous with Shuttle
ΔV_{soc-i}	-	Hohmann Transfer ΔV from SOC to satellite orbit
ΔV_{tot}	-	Ion propelled OTV ΔV from SOC to satellite orbit
Ω	-	Longitude of Right Ascension
ω	-	Argument of Perigee
τ	-	Thrust to mass ratio
τ_s	-	Synodic period

Abstract

This study examines a scenario for bolstering the operational control exercised over the U.S. satellite fleet. An Extended Space Transportation System (STS) composed of a Shuttle, Space Station, and Orbital Transfer Vehicle (OTV) is analysed using a nonlinear optimization technique. The OTV deploys a postulated fleet of military satellites across the entire gamut of inclinations and altitudes. The Shuttle payload mass and the total Station, OTV and Shuttle propellant mass required in orbit are calculated as a function of inclination and altitude, and used to minimize annual Shuttle launches. Launch rates for one, two and three Station scenarios are compared with the corresponding rates for current STS operations. The use of both chemically and ion propelled OTVs are evaluated. Applying a vector optimization process to the latter simultaneously minimizes both the average OTV mission duration and annual Shuttle launches. The resulting efficient operating frontier specifies a series of optimal inclinations, altitudes and OTV sizes at which the system should be operated. Total Shuttle launch rates for the Extended STS are significantly less than for direct orbital insertion of satellites with the Shuttle. Equally important, the ion propelled OTV satellite deployment times are probably fast enough to satisfy the military requirement of rapid deployment.

OPTIMIZING THE SPACE TRANSPORTATION SYSTEM

1.0 Introduction

In the past two decades the United States space program grew from a fledgling experiment to a fleet of operational satellites crucial to the civil and defense needs of the nation. The growing ability of military space systems to greatly enhance the effectiveness and reduce the cost of land, sea and air operations places them in the vanguard of United States operational forces. Space systems will be the first to identify an enemy attack should it occur, and they will be used to locate, deploy, command and control counter-attacking forces. The recent introduction of the Space Shuttle and the establishment of a USAF Space Command are important interim steps toward consolidating control over military satellite systems.

An operational Space Transportation System (STS) will greatly enhance the effectiveness of military satellites. Some potential benefits include: proliferating space systems thereby making them more difficult to negate, adding redundant subsystems to satellites to make them more reliable, adding shielding and other materials to make satellites less vulnerable to radiation and other forms of attack, and adding propellants to make satellites more maneuverable and to increase their mission duration (Ref. 1)

A top-level defense study chaired by former Secretary of the Air Force, Dr. Hans Mark, examined the utility of manned operations in space. The study envisioned the Shuttle being used to assemble large structures in space, to test military systems, to repair valuable spacecraft, to act as a command post during contingencies, and to be used for a variety of evolving missions. With the easy access of military personnel to orbit, the Air Force can develop new, less complex, and less expensive satellite systems specifically designed for orbital repair, refurbishment, service and retrieval (Ref 1).

Orbital service and test operations may eventually reduce factory and launch base test requirements, and give rise to a sequel to the Factory-to-Pad test concept employed with military satellites; namely, Factory-to-Orbit testing (Ref 2, p. 10). A NASA study published in 1974 examined the performance of 57 different spacecraft during the first month in orbit. A total of 154 malfunctions were noted with over 50% occurring on the first operational day. During the subsequent 29 days, there was a dramatic decrease in the number of daily failures (Ref 3). Manned systems like the Space Shuttle, capable of returning or repairing a satellite prior to final orbital insertion, should help to relieve the serious problem of spacecraft early on-orbit failures.

Although the Space Shuttle has great potential, it also has some inherent limitations. Unable to reach higher altitudes, its use for repair, refurbishment, service and retrieval operations is limited to Low Earth Orbit (LEO) satellites. The limited flight duration and cumbersome working environment further qualify the Shuttle's utility as an orbital work platform. The Shuttle's chief virtue is exactly what it was designed for--repetitively hauling large massive cargoes into LEO. Unfortunately, as currently employed the Shuttle cannot take full advantage of its cargo-hauling capabilities. Indeed, the Shuttle is seldom loaded to anywhere near capacity. A logical extension overcoming the Shuttle's drawbacks is the construction of a manned Space Operations Center (SOC) and Orbital Transfer Vehicle (OTV) to augment the STS. The Shuttle launched to a SOC could be consistently loaded with its maximum payload of cargo and OTV fuel.

As currently envisioned the Extended STS composed of the SOC, OTV and Shuttle would be the nexus binding together our national space assets. From the military perspective the SOC would serve as a central depot from which the satellite fleet could be managed. Some missions accomplished by the Extended STS might include:

1. To provide a depot for satellite checkout prior to final orbital deployment.
2. To provide a depot for satellite deployment, retrieval, test, service, refurbishment and repair.
3. To provide a base for a manned/unmanned reconnaissance fleet.

4. To provide a base allowing for rapid replenishment of pretested operational spacecraft.

5. To provide a base for an Anti-Ballistic Missile (ABM)/Anti-Satellite (ASAT) system.

These cardinal missions consolidate and bolster the operational control exercised over allied and enemy satellites. Although not exhaustive, these missions lend themselves to quantitative analysis.

2.0 Problem Statement

The Extended STS envisioned presents a transportation and logistics problem similar in principle to the determination of an optimal resupply scenario for remote forces. The Shuttle would deploy satellites, personnel, fuel and other consumables directly to the SOC. An OTV would then be used to deploy satellites to their final orbits. The Satellite Traffic Model which the OTV services is a hypothetical model which crudely reflects possible military traffic requirements between 1985 and 2000. Data within the model includes inclinations, altitudes, eccentricities, masses and launch frequencies for a fleet of postulated satellites (see Table 4.2). More realistic military models, compiled by Rockwell International (Ref 4), are available for authorized users. Since WWII such transportation problems have been routinely solved using linear programming techniques. The Extended STS differs from the traditional transportation problem in that the orbital equations used are nonlinear.

By utilizing nonlinear optimization techniques it is possible to determine an optimal orbit and resupply scenario for the SOC. The performance index used minimizes the mass of fuel consumed by OTV deployments, SOC orbit maintenance and the Shuttle Orbital Maneuvering System (OMS). This total fuel mass is calculated as a nonlinear function of inclination and altitude. Alternatively, the number of Shuttle launches can be minimized by dividing the total fuel mass by the payload mass of the Shuttle similarly calculated as a function of inclination and altitude. The SOC altitude and inclination are variables which the optimization procedure specifies. Constraints on the optimization process restrict the altitude and inclination to realizable values resulting in a positive payload mass and an OMS fuel tank capacity less than 10830 Kg. Both models are based on accurate assumptions, and both can be further refined.

The launch and fuel minimization models directly assess the launch and fuel costs associated with each component of the Extended STS. Of special significance is their ability to identify the costs associated with placing one SOC at a near equatorial inclination versus two SOCs, one each at polar and equatorial inclinations. The sensitivity or robustness of the model is analysed by varying parameters like the SOC ballistic coefficient, OTV mass and the engine specific impulses. The resulting impact on launch and fuel costs gives the engineer cost saving insight into efficient designs for an Extended STS. Minor changes to the models allow for an accurate assessment of the impact of increasing the specific impulses of the SOC and OTV engines into the range of the ion motor. With the completion of the sensitivity analysis several operational scenarios are evaluated.

One of the operational scenarios utilizes a vector optimization technique to minimize two performance indices: the number of Shuttle launches and the average flight time for an ion propelled OTV. The trade off between the number of launches versus the flight times provides an indication of whether current ion engine technology is sufficient to satisfy the military requirement of rapid deployment. In addition, a simplified ABM/ASAT system is postulated where the flight time to a coplanar target is minimized subject to a given characteristic velocity (ΔV). The latter problem is treated as an extension of the basic thesis, and not evaluated in detail.

The remainder of this thesis includes five sections explaining the solution methodology, results, summary, conclusion and recommendations. The former derives the six mathematical models used in the optimization program. Results of computer runs done for the different models are then tabulated and evaluated. A summary of the results compares the calculated Shuttle launch rates to the corresponding rates without an Extended STS. The concluding sections review the key findings, recommend additional research and recommend a tentative national space policy.

3.0 Solution Methodology

Minimization of the annual Shuttle launches or fuel consumption requires that the total mass transported to orbit be known. The total mass of the SOC, satellites and consumables is easily calculable from the Satellite Traffic Model and a few initial definitions. Similarly, the fuel mass consumed by the Shuttle OMS, SOC orbit maintenance and OTV engines is calculable with only a little extra effort. Combined, the mass of the SOC, satellites, consumables and propellant represents the total mass required to deploy, maintain and operate the Extended STS in orbit.

The mass of fuel used by the OMS and OTV engines can be calculated with the Rocket Equation:

$$\Delta V = Ig \times \ln\left(\frac{M_i}{M_o}\right) \qquad \text{(Eq. 3.1)}$$

where M_i and M_o are the masses before and after the ΔV maneuver. Specific impulse and gravitational acceleration are indicated by I and g respectively. Subtracting the final from the initial mass and substituting M_o and M_i from Eq. 3.1 gives the fuel mass (MF) consumed by the maneuver:

$$MF = M_i - M_o$$

$$MF = M_o(e^{\Delta V/Ig} - 1) \qquad \text{(Eqs. 3.2)}$$

$$MF = M_i\,(1 - e^{-\Delta V/Ig})$$

Consequently, the mass of propellant consumed is a function of I, g, ΔV and either the final or initial mass of the rocket. Alternatively, the annual SOC orbit maintenance fuel mass is calculated from the definition of specific impulse:

$$I = \frac{\text{Thrust}}{(dMF/dt) \times g}$$

$$dMF/dt = \frac{M \times A}{Ig} \qquad \text{(Eqs. 3.3)}$$

where M and A are the average mass and acceleration respectively. Although the units for the above equations are arbitrary, all of the calculations done in this study are in MKS units.

The major simplifying assumptions within the derived mass models include:

1. The SOC orbit is circular between 120 and 800 km.

2. The atmosphere is modeled as a rotating sphere whose density decreases exponentially with altitude.

3. Velocity changing maneuvers are modeled as impulsive Hohmann Transfers for the chemically propelled OTV.

4. The chemical OTV accomplishes a two impulse ΔV maneuver with the initial transfer being an altitude change to the destination orbit. A combined plane and altitude change then inserts the OTV into its destination orbit. To return to the SOC the same transfers are accomplished in the reverse order.

5. The outgoing and return ΔVs are assumed equivalent (actually, this study calculates the outgoing ΔV which is slightly greater than the return).

6. Each satellite within the Satellite Traffic Model is deployed individually by the OTV (a rigorously realistic scenario would allow for the simultaneous deployment of satellites whenever possible).

7. Realistic values are assumed for design parameters such as specific impulses, the SOC ballistic coefficient and the OTV mass.

8. The atmospheric scale height is assumed constant at 30 km (this gives an average atmospheric drag approximately equivalent to that experienced by Skylab--see Appendix B).

9. The generic Orbiter used is OV-99 (Challenger) with mass configuration and flight profile assumptions listed in Tables 3.1 and 3.2 respectively. Two assumptions inherent within the tables include not using any Reaction Control System (RCS) fuel during flight and the Orbiters return to Earth without any cargo on-board.

10. The gravitational acceleration (g) at an altitude of 390 km above the equator is used throughout this analysis, 8.7 m/sec^2.

11. The Orbiter ascent ΔV, deorbit ΔV and Main Engine Cut Off (MECO) mass are modeled by reqression analysis utilizing flight planning data.

12. A military Satellite Traffic Model for deploying new satellites is postulated, while the satellite retrieval mission for repair and refurbishment is ignored.

All of the assumptions used to derive the mass models are extremely good approximations, and usually reflect a slightly high estimate of the mass needed in orbit. Although it would be superfluous to the purposes of this study, many of the assumptions could be further refined or eliminated with more elaborate models and a more accurate assessment of the current STS capabilities.

3.1 OMS Propellant Consumption

In deriving an expression for the OMS propellant consumption it is necessary to calculate the inserted mass at MECO. The masses for various inclinations are estimated with NASA flight planning data (Ref 5). Derived MECO masses are tabulated in Appendix A and modeled as a function of inclination (I_{soc}-measured in degrees) by linear regression analysis. The maximum 3-sigma error associated with each MECO mass calculation is estimated to 148 Kg and 245 Kg for the Eastern and Western Test Ranges (ETR & WTR) respectively. The corresponding correlation coefficients are greater than 0.99999 for both cases. The resulting equations measuring mass in kilograms are:

$$MM_{etr} = 159275.829 + 3.3575 \times I_{soc} - 3.70994 \times I_{soc}^2 + 0.01339 \times I_{soc}^3$$

$$MM_{wtr} = 164628.209 - 79.17494 \times I_{soc} - 3.01734 \times I_{soc}^2 + 0.01256 \times I_{soc}^3 \qquad \text{(Eqs. 3.4)}$$

$$M_{et} = 38399.0$$

The variables MM_{etr} and MM_{wtr} designate the inserted MECO mass from the ETR and WTR, while Met designates the mass of the Space Shuttle External Tank (ET), residual fuel and propellant required for ET Separation (ETS). Table 3.1 delineates the mass configuration of the generic Orbiter used to resupply the SOC. The STS configuration and assumptions made in calculating the MECO masses are shown in Table 3.2. Care was taken to insure that all assumptions were conservative estimates for the postulated STS configuration. Consequently, Eqs. 3.4 represent conservative estimates of the Shuttle fleet's capability to nominal MECO when outfitted with HPM WTR Motors and 82945 Kg (inert mass) Solid Rocket Motors (SRM). Challenger was chosen as the generic Orbiter because of its median mass with respect to the other vehicles.

Two other quantities modeled by linear regression analysis are the characteristic velocities required for Orbiter ascent from MECO (ΔVA) and Deorbit (ΔVD). The data for the regression analysis was generated by the ascent and deorbit ΔV equations in Appendix A. The Appendix A equations are used by NASA JSC personnel for mission planning (Ref 6) and include a velocity reserve for contingencies.

Table 3.1 Mass Configuration of Generic Orbiter (based on STS-7 mission)

ITEM		MASS (Kg)
Capability to Nominal MECO	+	MM
OMS Propellant (Ascent)	-	MF_{oa}
OMS Propellant (Deorbit)	-	MF_{od}
Orbiter OV-99 Inert	-	68346
Space Shuttle Main Engines (SSME)	-	9461
Non Propulsive Consumables	-	2166
STS mass charges to operator	-	2588
Personnel (2 Men/6 Days)	-	813
RCS Propellant	-	3306
STS Operations Reserve	-	1361
SUBTOTAL (reference mass-M_r)	-	88041
RCS Propellant for ET Separation	-	100
MPS Unusable Fluids	-	3991
MPS Flight Performance Reserve	-	2518
External Tank (Block II)	-	31790
SUBTOTAL (Mass at ETS-Met)	-	38399
Payload Mass	=	M_{pl}

Table 3.2 Flight Profile Assumptions for MECO Mass Calculation

ETR Launch	WTR Launch
-Std MECO Conditions	-Std MECO Conditions
-Altitude = 57 NM	-Same
-Flt Path Angle=0.65°	-Same
-Iner. Vel = 25680 fps	-Iner. Vel = 25374 fps
-102% SSME Power Level	-Same
-2.75 Sec delay till SRM Ignition	-Same
-3σ Flight Performance Reserve	-Same
-15 July Launch	-15 March Launch
-680 PSF Pressure	-650 PSF Pressure
-HPM WTR Motor	-Same
-Light Weight SRM	-Same
-Light Weight ET	-Same
-OV-99 (see Table 3.1)	-Same

$$\Delta VA_{etr} = (-2.023703587 \times 10^{-5}) \times R_{soc}^2$$

$$+ 0.8474467398 \times R_{soc} - 4623.658232$$

$$\Delta VA_{wtr} = \Delta VA_{etr} + 85.65 \text{ m/s} \qquad \text{(Eqs. 3.5)}$$

$$\Delta VD = (1.974610171 \times 10^{-4}) \times R_{soc}^2$$

$$- 2.50173195 \times R_{soc} + 7994.436744$$

The correlation coefficients calculated in Appendix A are 0.99999 for ascent and 0.99696 for deorbit. It is worth noting that the ascent ΔVs could be calculated exactly by using the ETR and WTR standard MECO conditions shown in Appendix A. Similarly, a good estimate for the deorbit ΔV could be calculated by targeting the maneuver's perigee for a constant altitude within the atmosphere.

Utilizing the curve-fitted data and Eqs. 3.2 the Shuttle OMS fuel consumption for ETR launches is:

$$MF_{oa} = (MM_{etr} - M_{et})(1-e^{(-\Delta VA_{etr}/Ig)})$$

(Eqs. 3.6)

$$MF_{od} = (MM_{etr} - M_{et} - MF_{oa} - M_{pl})(1-e^{(\Delta VD/Ig)})$$

where M_{pl}, MF_{oa} and MF_{od} are the Orbiter payload mass, the propellant mass required for Orbiter ascent and the propellant mass required for deorbit. The payload mass of the Orbiter is calculable if the Orbiter reference mass

(M_r), calculated in Table 3.1, is known (M_r is approximately equal to the Orbiter reentry mass):

$$M_{pl} = MM_{etr} - M_{et} - MF_{oa} - MF_{od} - M_r \qquad \text{(Eq. 3.7)}$$

Solving Eqs. 3.4, 3.6 and 3.7 simultaneously for the payload mass yields:

$$M_{pl} = (MM_{etr} - M_{et})e^{(-\Delta VA_{etr}/Ig)} - M_r \times e^{(\Delta VD/Ig)} \qquad \text{(Eq. 3.8)}$$

The WTR equations corresponding to Eqs. 3.6, 3.7 and 3.8 are easily derived by substituting MM_{wtr} and ΔVA_{wtr} for MM_{etr} and ΔVA_{etr}. All three equations are predicated on not using any RCS propellant during flight. This assumption is reasonable with careful mission planning, and even when ignored results only in a conservatively high estimate of the OMS propellant mass consumed in orbit.

3.2 SOC Orbit Maintenance Propellant Consumption

The mass of SOC orbit maintenance propellant can be estimated by first calculating the acceleration due to air drag. From the definition of impulse:

$$D \times dt = M_{soc} \times dV_{soc}$$

or

$$A_{soc} = D/M_{soc} = P \times F \times S \times C_d \times V_{po}^2/2M_{soc} \qquad \text{(Eq. 3.9)}$$

where A_{soc} is the acceleration of the SOC due to air drag (D). The individual drag terms are defined in King-Hele (Ref 7, p70p. 20-26) as:

$C_d \sim 2.2$ = drag coefficient

S = average cross sectional area

M_{soc} = mass of SOC

$B = (C_d S)/M_{soc}$ = ballistic coefficient (m^2/kg)

$F = f(R_{po}, I_{soc}) = (1 - R_{po} x W_e x \cos(I_{soc}))/V_{po})^2$ $\quad 20^o < I_{soc} < 90^o$

$F = 2 - f(R_{po}\ , 180^0 - I_{soc})$ $\quad 90^o < I_{soc} < 180^o$

$F = 0.00175 \times I_{soc} + 0.84004$ $\quad 25^o < I_{soc} < 180^o$

$R_{po} = R_{soc}$ = perigee/SOC radius (Eqs. 3.10)

I_{soc} = SOC inclination

$V_{po} = (U/R_{soc})^{1/2}$ = perigee velocity

$W_e = 7.292115856 \times 10^{-5}$ rad/sec = earth's angular velocity

$U = 398601.2\ km^3/sec^2$ = gravitational parameter

$P = P_o \times e^{((R_o - R_{soc})/H)}$

R_o = 120 km = reference altitude

R_o = 120 km = reference altitude

P_o = 24.9 Kg/km^3 = atmospheric density at R_o

H = 30.0 km = scale height

The equation specified by F represents the effect of atmospheric rotation on drag, and varies between about 0.9 and 1.1 over the inclination range. This rotating atmosphere factor is shown for inclinations below and above 90°, and is also modeled by regression analysis for the inclination range of interest. The extreme sensitivity of the atmospheric model resulted in unrealistically high estimates of fuel consumption when a linear fit to the Scale Height was attempted. Consequently, the constant value of Scale Height was chosen which resulted in an atmospheric drag approximately equal to that experienced by the Skylab mission (see Appendix B). Substituting the terms of Eqs. 3.10 into Eq. 3.9 gives:

$$A_{soc} = U \times P_o \times B \times (0.00175 \times I_{soc} + 0.84004) \times \frac{e^{(R_o - R_{soc})/H}}{2R_{soc}} \qquad \text{(Eq. 3.11)}$$

and utilizing Eq. 3.3:

$$MF_{soc} = (M_{soc} \times A_{soc})\ 31557600/Ig \qquad \text{(Eq. 3.12)}$$

where MF_{soc} is the average annual mass of propellant required to keep the SOC in orbit.

3.3 OTV Propellant Consumption

The OTV propellant mass required to deploy or retrieve a satellite is derived by first calculating the required ΔV. Figure 3.1 depicts the two-impulse Hohmann Transfer used by the maneuver. The first impulse accomplishes an altitude change to the mission orbit's apogee, then a combined inclination and altitude change places the OTV in its destination orbit.

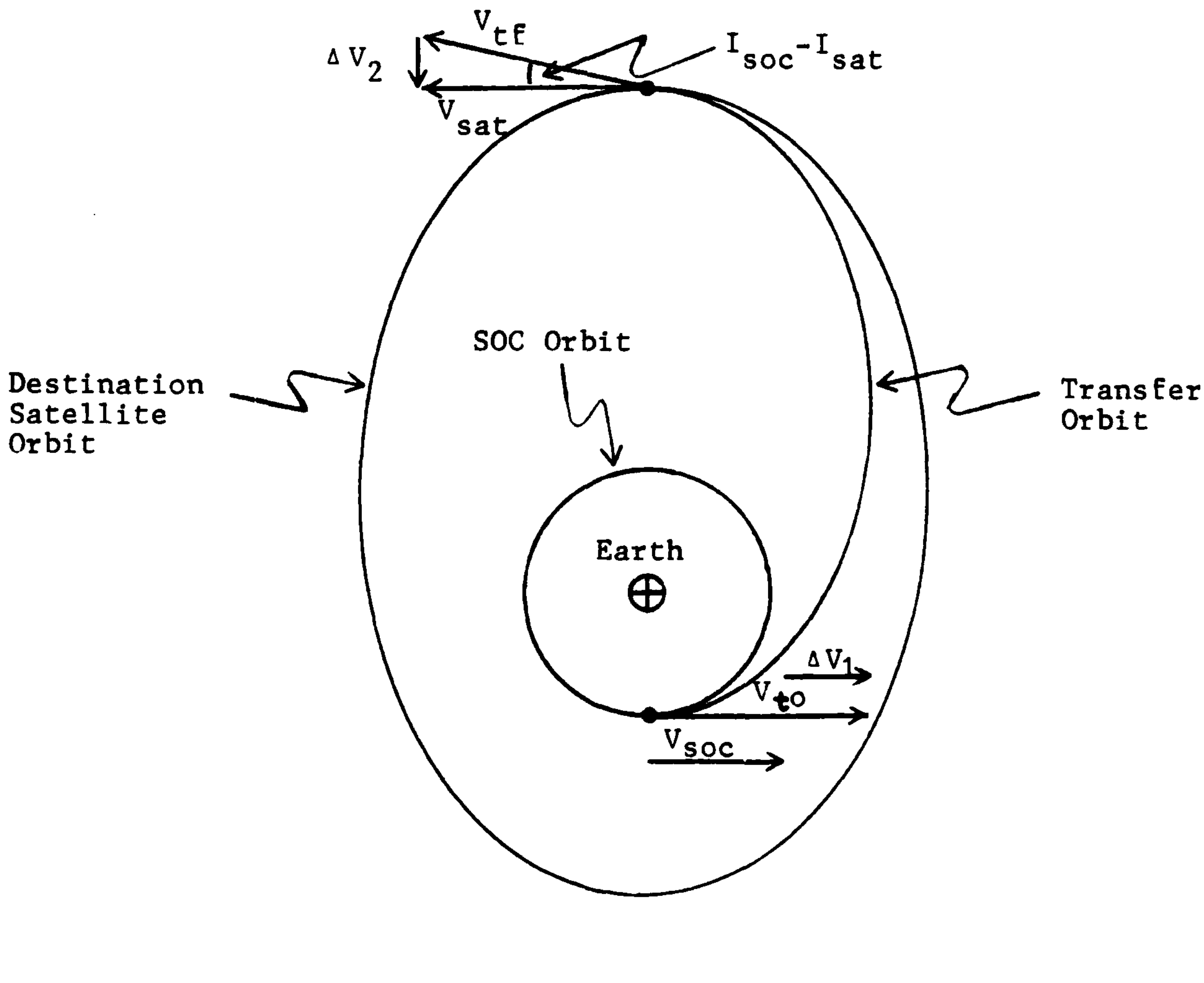

Fig 3.1 Hohmann Transfer

The equations for the first impulse are:

$$V_{soc} = (U/R_{soc})^{1/2}$$

$$V_{to} = (2U(1/R_{soc} - 1/(R_{asat} + R_{soc}))^{1/2}$$

(Eqs. 3.13)

$$R_{asat} = A_{sat}(1 + e_{sat})$$

$$\Delta V_1 = V_{to} - V_{soc}$$

and for the second impulse:

$$V_{tf} = (2U(1/R_{asat} - 1/(R_{asat} + R_{soc}))^{1/2}$$

$$V_{sat} = (2U(1/R_{asat} - 1/2A_{sat}))^{1/2} \qquad \text{(Eqs. 3.14)}$$

$$\Delta V_2 = (V_{tf}^2 + V_{sat}^2 - V_{tf} \times V_{sat} \times \cos(I_{soc} - I_{sat}))$$

Recognizing that the ΔV required to travel from the SOC to the satellite mission orbit is approximately equal to the return ΔV ($\Delta V_{soc-1} \sim \Delta V_{I-soc}$) , and combining Eqs. 3.13 and 3.14:

$$\Delta V_{soc-i} = \Delta V_1 + \Delta V_2 \qquad \text{(Eq 3.15)}$$

Solving Eqs. 3.2 and 3.15 simultaneously gives the total mass of fuel required to service a satellite orbit with inclination (I_{sat}) , semi-major axis (A_{sat}) , eccentricity (e_{sat}) and satellite mass (M_{sat}) :

$$MF_{rtn} = M_{otv}(e^{(\Delta V_{soc-i}/Ig)} - 1)$$

(Eqs. 3.16)

$$MF_{dpl} = (M_{sat} + M_{otv} + MF_{rtn})(e^{(\Delta V_{soc-i}/Ig)} - 1)$$

where M_{otv} is the OTV mass, MF_{dpl} is the propellant mass required to deploy a satellite and MF_{rtn} is the propellant mass required to return to the SOC. Summing the two equations:

$$MF_{msn} = (M_{sat} + M_{otv} + M_{otv} \times e^{(\Delta V_{soc-i}/Ig)})$$

$$\times (e^{(\Delta V_{soc-i}/Ig)} - 1) \qquad \text{(Eq. 3.17)}$$

where MF_{msn} is the mass of propellant required per OTV mission depolying a payload and returning to the SOC.

3.4 Calculation of Launch Windows

The Hohmann Transfer specifies all of the orbital elements except the argument of perigee (ω) and the longitude of right ascension (Ω). Both parameters can be set by choosing an appropriate launch window for the OTV. Alternatively, the frequency at which launch windows occur can be calculated if the SOC and satellite orbits are known. The window occurs once during each synodic period of the satellite and SOC argument of perigee. Similarly, the window occurs twice during each synodic period of the satellite and SOC longitude of right ascension. The ω window occurs much more frequently than the corresponding Ω window which is calculated from the definition of synodic period (τ_S):

$$\tau_S = \frac{\pi}{d\Omega_{sat}/dt - d\Omega_{soc}/dt}$$

$$d\Omega_{sat}/dt = \frac{-3 \times J2 \times \cos(I_{sat}) \times (U/A^{7}_{sat})}{2(1 - e^{2}_{sat})^{2}} \qquad \text{(Eqs. 3.18)}$$

$$d\Omega_{soc}/dt = -3 \times J2 \times \cos(I_{soc}) \times (U/R^{7}_{soc})$$

$$J2 = 0.001082642 \quad \text{(Ref 8, p. 422)}$$

where J2 is a constant, and $d\Omega_{sat}/dt$ and $d\Omega_{soc}/dt$ are the time rates of change of the longitude of right ascension for the satellite and SOC respectively. Similarly, Eqs. 3.18 could be used to calculate the synodic period between the satellite and SOC argument of perigee by replacing $d\Omega_{sat}/dt$ and $d\Omega_{soc}/dt$ with the satellite and SOC orbital rates. However, since the propellant cost associated with orbital transfers to a less than optimal ω is negligible in comparison with similar Ω transfers they are ignored in this analysis.

Besides being useful for deriving launch windows, the time variation of right ascension might also be useful for deploying spare orbital satellites or even an ABM/ASAT system. Objects deployed at the SOC inclination but with a different altitude have different nodal regression rates and, consequently, different ground tracks over the surface of the Earth. Spare satellites deployed in this manner are geographically dispersed over the surface of the Earth, and yet easily serviced at periodic intervals with only a small coplanar Hohmann Transfer from the SOC. An ASAT system deployed similarly has two coplanar intercept opportunities during each orbit of a target satellite. The corresponding ABM scenario is more complex in that there is only one launch opportunity, and consequently many more interceptors are required. The geographic dispersal of all the systems makes them difficult targets which must be destroyed one at a time.

3.5 Single Objective Optimization Problems

Several nonlinear optimization problems are posed and solved utilizing a numerical routine, the Sequential Unconstrained Minimization Technique (SUMT) computer program (Ref 9). This program uses a penalty function approach to find the minimum of a single multivariable nonlinear function (called an objective function or performance index) subject to inequality and equality constraints:

MIN: $F(X_1, X_2, \ldots, X_n)$

SUBJECT TO CONSTRAINTS:

$$G_k(X_1, X_2, \ldots, X_n) > 0$$

$$k = 1, 2, \ldots, M$$

$$H_k(X_1, X_2, \ldots, X_n) = 0$$
$$k = M + 1, M + 2, \ldots, M + MZ$$

The procedure, developed by Fiacco and McCormick (Ref 10), uses the problem constraints and the original objective function to form an unconstrained objective function which is minimized by any appropriate unconstrained multivariable technique. A requirement on the F, G and H functions is that they be continuous and twice differentiable. Fig 3.2 is a brief flowchart of the SUMT algorithm. The performance indices individually minimized by SUMT include the total fuel consumption and number of Shuttle launches for an Extended STS.

3.5.1 Model I--ETR/WTR Fuel Minimization Model

With all of the propellant mass terms defined, the minimization problem is:

$$\text{MIN:} \quad MF_{tot} = F_{orb} \times (MF_{oa} + MF_{od}) + MF_{soc} + \sum_{i=1}^{n} (F_{sat} \times MF_{msn})$$

SUBJECT TO CONSTRAINTS: (Eqs. 3.19)

$28.5^\circ < I_{soc} < 57^\circ$	ETR Inclination constraint
$56^\circ < I_{soc} < 104^\circ$	WTR Inclination constraint
$6500 \text{ km} < R_{soc} < 7200 \text{ km}$	Altitude constraints
$MF_{oa} + MF_{od} < 10830 \text{ Kg}$	OMS fuel constraint
$M_{pl} > 0 \text{ Kg}$	Orbiter payload constraint
I_{soc}, R_{soc}	Problem variables

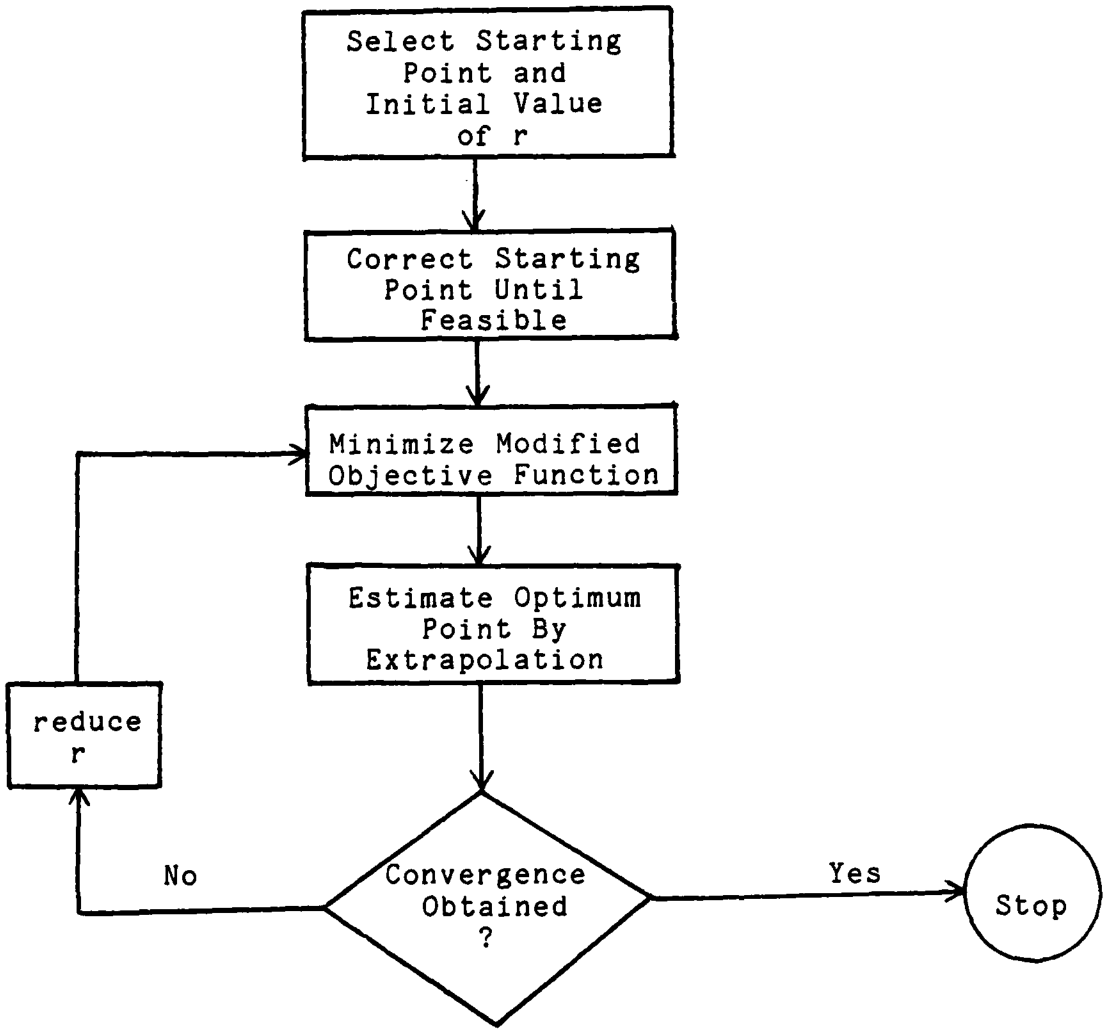

Fig 3.2 Fiacco and McCormick (SUMT Algorithm) Logic Diagram

where all terms have been previously defined except the annual satellite launch frequency (F_{sat}), the total fuel consumption (MF_{tot}), the number of satellite missions (n) and the number of Shuttle launches (F_{orb}). The latter can either be estimated or calculated more rigorously by:

$$F_{orb} = \frac{\sum_{i=1}^{n} [F_{sat} \times (M_{sat}+MF_{msn})] + MF_{soc} + M_c}{M_{pl}} \qquad \text{(Eq. 3.20)}$$

where M_c includes the mass of the SOC, OTVs and consumables (food, oxygen, men, equipment, etc.) required to build and operate the station. Some estimates of the required masses are: (Ref 11, p. 189):

M_{soc} & M_{otv} ~ 100000 Kg

M_{food} ~ 210 Kg/yr/man

M_{water} ~ 765 KG/yr/man

M_{air} ~ 330 KG/yr/man

M_{misc} ~ 5920 Kg/yr

Averaging the above for a six man station over a 16 year period gives an M_c of 20000 Kg/yr.

3.5.2 Model II--ETR/WTR Launch Minimization Model

As an alternative to the fuel minimization problem the number of Shuttle launches are also minimized.

$$\text{MIN:} \quad F_{orb} = \frac{\sum_{i=1}^{n} [F_{sat}(M_{sat} + MF_{msn})] + MF_{soc} + M_c}{M_{pl}}$$

SUBJECT TO CONSTRAINTS: (Eqs. 3.22)

$28.5^o < I_{soc} < 57^o$	ETR constraint
$56^o < I_{soc} < 104^o$	WTR constraint
$6500 \text{ km} < R_{soc} < 7200 \text{ km}$	Altitude constraint
$MF_{oa} + MF_{od} < 10830 \text{ Kg}$	OMS fuel constraint
$M_{pl} > 0 \text{ kg}$	Payload constraint
I_{soc}, R_{soc}	Problem Variables

3.5.3 Model III--ETR/WTR Launch Minimization Model with OTV/Shuttle Rendezvous in LEO

One possible method of further reducing the number of Shuttle Launches is to deploy the OTV to a low altitude where it would rendezvous with the Shuttle. After rendezvous the OTV would pick up the Shuttle payload and sufficient fuel for the return journey to the SOC. Although manned and unmanned cargo modules would be needed, they should not be difficult to build and could be reused. Alternatively, the necessity for manned modules could be eliminated by occassionally deploying the Shuttle all the way to the SOC for personnel changes.

To implement the changes to Model II a Hohmann Transfer is calculated from the rendezvous inclination and altitude to the SOC. The rendezvous inclination is left as a variable, while the altitude is set at the maximum altitude attained by the Shuttle during ballistic flight after MECO (i.e. the apogee altitude for the standard MECO conditions). The Shuttle rendezvous radius, and the corresponding ascent and descent ΔVs are:

$$R_{ren} = 6538.1 \text{ km (Altitude = 160 km)}$$

$$I_{ren} = \text{variable}$$

$$\Delta VA_{etr} = 51.7 \text{ m/sec} \qquad \text{(Eqs. 3.23)}$$

$$\Delta VA_{wtr} = 137.4 \text{ m/sec}$$

$$\Delta VD = 84.1 \text{ m/sec}$$

where R_{ren} and I_{ren} are the rendezvous altitude and inclination. The values of ΔVA and ΔVD were calculated utilizing Eqs. 3.5. Substituting into Eqs. 3.13, 3.14 and 3.15 R_{ren} for R_{soc}, and R_{soc} for R_{asat} and A_{sat}, the Hohmann Transfer characteristic velocity (ΔV_{ren}) is calculable. Utilizing Eqs. 3.2, 3.23 and ΔV_{ren} the fuel mass required for the OTV to descend to (and ascend from) the rendezvous orbit is calculated as follows:

$$MF_{dsc} = M_{otv} \times (e^{(\Delta V_{ren}/Ig)} - 1)$$

$$\text{(Eqs. 3.24)}$$

$$MF_{asc} = (M_{otv} + M_{pl}) \times (1 - e^{(-\Delta V_{ren}/Ig)})$$

where all of the variables except V_{ren}, MF_{dsc} and MF_{asc} are defined as in Eqs. 3.16. The last minor change to the model requires the addition of MF_{dsc} into the numerator, and the subtraction of MF_{asc} from the denominator of Eq. 3.20 The resulting Orbiter launch frequency is:

$$F_{orb} = \frac{\sum_{i=1}^{n} [F_{sat}(M_{sat}+MF_{msn})] + MF_{soc} + M_c + MF_{dsc} x F_{orb}}{(M_{pl} - MF_{asc})}$$

(Eq. 3.25)

Simplified and restated the minimization problem becomes:

$$\text{MIN:} \quad F_{orb} = \frac{\sum_{i=1}^{n} [F_{sat}(M_{sat}+MF_{msn})] + MF_{soc} + M_c}{(M_{pl} - MF_{dsc} - MF_{asc})}$$

SUBJECT TO CONSTRAINTS: (Eqs. 3.26)

(same as in Eqs. 3.22 except I_{ren} is also a variable)

3.5.4 Model IV--ETR/WTR Launch Minimization Model with Ion Propelled OTV

Due to the high fuel cost of deploying satellites with the OTV more efficient engine designs may be desirable. A likely candidate is the ion engine which can deploy payloads with vastly less fuel than required by a chemical vehicle. The major drawback of the ion system is its very low thrust which results in lengthy missions. Unfortunately, the

Hohmann Transfer yields an optimistically low estimate of the velocity change required for constant low thrust orbit changes.

A better model partially developed at the Air Force Institute of Technology requires the deletion of assumptions 3, 4 and 5 of Section 3.0 and the addition of two new assumptions:

1. Propulsion system thrust is low requiring an infinite number of revolutions to reach the final orbit.
2. The radius change is accomplished first followed by the inclination change.
3. The ion OTV mass is approximated with Eq. 3.30.

Applying these assumptions Alfano and Wiesel derived minimum flight times for radius and plane changes accomplished independently (Ref 12):

$$a_o^{-1/2} - a_f^{-1/2} = \tau \times t \times U^{-1/2}$$

(Eqs. 3.27)

$$I_o - I_f = \frac{2\tau \times t \times (a/U)^{1/2}}{\pi}$$

The semimajor axis and inclination are designated by a and I, while τ and t represent the thrust to mass ratio and the mission duration. The gravitational parameter is represented as before by U. The same investigators also successfully evaluated combined plane and radius changes which were slightly more efficient, but their implementation is much more complex.

Applying Eqs 3.27 to the OTV orbit change gives ΔVs for the outgoing and return trips:

$$\Delta V1 = A_{sat}^{-1/2} - R_{soc}^{-1/2}$$

$$\Delta V2 = \frac{\pi}{2} \times \left| I_{sat} - I_{soc} \right| \times A_{sat}^{-1/2} \qquad \text{(Eqs. 3.28)}$$

$$\Delta V_{tot} = \Delta V1 + \Delta V2$$

where ΔV_{tot} represents the total velocity change required in canonical units. These ΔV equations can be used as in Eq. 3.16 to define the fuel mass required to deploy and retrieve satellites:

$$MF_{rtn} = M_{otv} \times (e^{(\Delta V_{tot}/Ig)} - 1)$$

(Eqs. 3.29)

$$MF_{dpl} = (M_{otv} + M_{sat} + MF_{rtn}) \times (e^{(\Delta V_{tot}/Ig)} - 1)$$

where all of the variables except ΔV_{tot} are defined as in Eq. 3.16. An interesting alternative to using a constant OTV mass is to define the mass in terms of the number of ion thruster used (Ref 13, p. 82):

$$M_{otv} = N \times (M_{thr} + M_{sp} \times P_{wr} + M_{ft}) + M_{str} \qquad \text{(Eq. 3.30)}$$

where N, M_{thr}, M_{sp}, P_{wr}, M_{ft} and M_{str} are the number of thrusters, thruster mass, specific mass, thruster power, fuel tank mass and the mass of the OTV structure and control systems respectively.

Deployment and return times for the OTV can be calculated by integrating the mass flow rate, Eq. 3.3:

$$dMF/dt = (N \times T)/Ig$$

or

$$TIM = (MF \times Ig)/N \times T \qquad \text{(Eq. 3.31)}$$

The flight time, TIM, is thus easily calculable once the required fuel mass and individual motor thrusts, T, are known. Applyng Eqs. 3.31 and 3.29 allows for the calculation of the OTV deployment and return times for each mission within the Satellite Traffic Model:

$$TIM_{rtn} = MF_{rtn} \times Ig/(N \times T)$$

$$TIM_{dpl} = MF_{dpl} \times Ig/(N \times T) \qquad \text{(Eq. 3.32)}$$

where TIM_{rtn} and TIM_{dpl} represent the return and deployment times respectively.

The resulting problem is identical to the ETR/WTR Launch Minimization problem in section 3.5.2, except that the ΔVs required for OTV orbital changes are defined by Eqs. 3.28. In addition, the OTV flight times are defined, and could be minimized in place of the number of STS launches. Utilizing Eq. 3.30 and varying the ion engine design parameters also provide insight into the feasibility of an ion propelled OTV for rapid satellite deployment.

3.5.5 Model V--ETR/WTR Launch Minimization Model with Chemical OTV/STS Rendezvous in LEO and Ion OTV for Satellite Deployment

The final "operational" scenario considered combines the methods of sections 3.5.3 and 3.5.4. A chemical OTV is again used to rendezvous with the Shuttle and pick up payload and fuel for the return journey. Concurrently, ion-propelled OTVs deploy satellites to their operational orbits. The final minimization problem is identical to that in section 3.5.3, except the ion-propelled OTV mass, delta-vees and mission durations are calculated by Eqs. 3.30, 3.28 and 3.32 respectively. Also, the OTV rendezvous inclination is set equal to the SOC inclination to reduce the number of variables. The resulting two variable problem is considerably easier for the numerical technique SUMT to optimize.

3.6 Multiple Objective Optimization Problems

In addition to problems containing only one objective function, similar problems can be formulated with a vector of several objective functions. A vector or multiple objective optimization technique optimizes the vector of objective function with a comuter program such as PROCES. The procedure (Ref. 14,15,21 & 22) sequentially minimizes each objective function subject to the original problem constraints and internally imposed equality constraints due to the remaining objective functions. The sequential minimization problem is accomplished by using the SUMT optimization program as a subroutine within PROCES.

The solution of the problem is a Non-Dominated Solution Set (NDSS) known as an efficient frontier. Specific values for the problem variables (for example SOC inclination, radius, etc.) are associated with each point of the NDSS. Figure 3.3 shows a dual objective optimization scheme where each axis represents a performance index, J1 or J2.

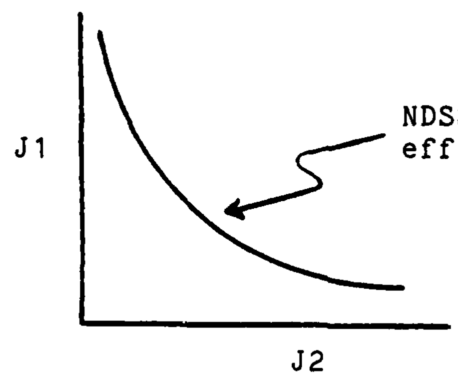

Fig. 3.3 Dual Objective Optimization Scheme

In the two dimensional case the solution is analogous to the guns vs. butter dichotomy commonly cited in economic theory. However, PROCES allows the user to find the actual values of points on the efficient frontier.

Two problems with dual objective functions lend themselves to vector optimization solutions. The first is a variation of the launch minimization models of Section 3.5. However, in addition to the number of Shuttle launches the average ion-propelled OTV Time-of-Flight (TOF) is minimized. A second vector optimization application may provide a means to evaluate an ABM/ASAT system. The ABM/ASAT TOF is minimized subject to different ΔV and/or true anomaly constraints.

3.6.1 Model VI--Minimized Shuttle Launches vs Average Ion-Propelled OTV Time of Flight

Keeping the number of Shuttle launches to a minimum is not the only important consideration when designing an Extended STS. For the case of an ion propelled OTV the vehicle's average TOF is often equally important. A TOF measured in years contravenes the occasional military requirement for rapid deployment. Adoptance of an on-orbit spares philosophy, whereby inactive operational satellites are deployed in advance of need, partially obviates the military requirement for rapid deployment. However, engineering common sense and the satellite lifetime dictates that transit time be kept to a minimum.

When the average TOF for OTV missions and the number of Shuttle launches are simultaneously minimized a graph similar to Fig. 3.3 is generated. The graph depicts the minimum number of Shuttle launches as a function of the average TOF for OTV missions. The relationship between the TOF and STS launches (called the NDSS or efficient frontier) provides the designer with an important decision-making tool; namely, a trade off analysis between cost (STS launches) and operational utility (TOF).

Application of a vector optimization technique to ETR Model V is a relatively straight forward procedure. The resulting dual objective minimization problem is:

$$\text{MIN: } F_{orb} = \frac{\sum_{i=1}^{n}[F_{sat} x (M_{sat} + MF_{dpl} + MF_{rtn})] + MF_{soc} + M_c + NO x M_{otv}}{M_{pl} - MF_{asc} - MF_{dsc}}$$

and

$$TIM_{avg} = \frac{\sum_{i=1}^{n}(TIM_{dpl} + TIM_{rtn})}{n}$$

SUBJECT TO CONSTRAINTS: (Eqs. 3.33)

$28.5^0 < I_{soc} < 57^o$	ETR constraint
$6500 \text{ km} < R_{soc} < 7200 \text{ km}$	Altitude constraint
$MF_{oa} + MF_{od} < 10830 \text{ kg}$	OMS fuel constraint
$M_{pl} > 0 \text{ kg}$	Payload constraint
$N > 0$	Number of ion thrusters
$NO > 0$	Number of OTVs
I_{soc}, R_{soc}, N	Problem variables

Although most of the expressions in the model are standard a few new ones appear and several need clarification.

The new expressions include TIM_{avg} and NO which respectively represent the average TOF for an ion propelled OTV and the average number of OTVs required to service the Satellite Traffic Model. The average TOF is calculated above while NO is given by:

$$NO = \frac{(TIM_{dpl} + TIM_{rtn})F_{sat}}{365.25} \qquad \text{(Eq. 3.34)}$$

Because TIM is measured in days/mission and F_{sat} in missions/year the 365.25 days/year conversion factor must be included. The quantities MF_{dpl} and MF_{rtn} represent the fuel mass consumed by the ion-propelled OTV, while MF_{asc} and MF_{dsc} represent the fuel mass consumed by the chemically propelled OTV when rendezvousing with the Shuttle.

The ion-propelled OTV mass is again calculated by Eq. 3.30:

$$M_{otv} = N \times (M_{thr} + M_{sp} \times P_{wr} + M_{ft}) + M_{str}$$

However, unlike the previous case the number of ion thrusters, N, is left as a variable which the optimization procedure specifies. Consequently, this problem has three variables: SOC inclination, SOC radius and the number of ion thrusters on the OTV.

3.6.2 Model VII--Minimized ABM/ASAT Time of Flight

Optimizing the Extended STS is not the only useful vector optimization application. The technique might also be applied to minimize the TOF to a target satellite or ballistic missile. To simplify the problem only coplanar transfers are considered with intercept occurring at the node connecting the interceptor and target orbits. It is possible to intercept target satellites frequently by deploying a string of interceptors at the same inclination as the SOC. An altitude difference between the SOC and interceptor orbit specifies the nodal regression rate between the SOC and interceptor longitude of ascending nodes. Consequently, an OTV based at the SOC could service the interceptor orbit at periodic intervals with only a small altitude change. The service interval for the OTV is the synodic period between the two nodal regression rates and is calculated by Eqs. 3.18.

An ASAT system deployed in this manner has two coplanar intercept opportunities during each orbit of a target satellite. The ABM scenario is much more complex in that a variety of different interceptor orbits are probably required. The ABM interceptors would have to be deployed at different inclinations in order to intercept both ICBMs and SLBMs. Further, the Earth's rotation (and therefore the rotation of potential launch sites) requires that the interceptors at a given inclination be deployed at different Longitudes of Right Ascension.

Although the ABM system is considerably more complex than an ASAT system it has the added advantage of possibly being useful against airborne, ground and naval targets.

Minimizing the TOF is fairly simple when applied to a specific case (Ref. 8, p. 181). However, the general case is considerably more complex. Applying a vector optimization technique to the problem might allow for the simultaneous minimization of interceptor TOF, ΔV and true anomaly at epoch. In essence, the solution would be a NDSS with TOF given as a function of ΔV and/or true anomaly. The transfer orbit parameters would be problem variables specified by the optimization procedure. These values indirectly specify the mass and quantity of ABM/ASAT interceptors required to achieve a given TOF. The problem is not simple but a successful solution would allow decision-makers to quantify the cost and effectiveness of spaceborne interceptors in future conflicts. Such a solution may be well worth the invested effort.

4.0 Results

Numerous computer runs were completed on Models I through VI of Section 3.0. Model VII was analysed qualitatively but not implemented on the computer. Appendix D contains a listing of the operational computer runs accomplished and selected outputs. In addition to the operational runs of Appendix D several test runs were completed on the basic fuel and launch minimization models. Table 4.1 lists the standard problem parameters which were used in the test and operational computer runs. Variation of these parameters in the operational runs provided insight into the best means of designing an Extended STS. Table 4.2 shows the Satellite Traffic Models used for the test and operational runs.

4.1 Model Validation

Validation of the basic model was accomplished by applying the ETR model to three test missions. The missions shown in Table 4.2 include orbital parameters, masses and launch frequencies for three satellites. The SUMT minimization program was run with one, two and then all three test missions used as data. In each case, five different performance indices were minimized. The Orbiter, OTV and SOC orbit maintenance fuel consumption were minimized individually. Then the combined (Extended STS) fuel consumption and the number of Shuttle launches were

Table 4.1 Standard Parameter Configuration

SOC Ballistic Coefficient (m^2/kg)	=	0.02
Atmospheric Scale Height (km)	=	30.00
OTV Mass (kg)	=	2270.00
SOC and OTV Fleet Mass (kg)	=	100000.00
Annual SOC Cargo Mass (kg/yr)	=	20000.00
Chemical OTV Engine Specific Impulse (sec)	=	455.00
Chemical SOC Engine Specific Impulse (sec)	=	455.00
ORB Specific Impulse (sec)	=	313.00
Expended Mass at ETS (kg)	=	38399.00
Shuttle Reference Mass (kg)	=	88041.00
Ion Thruster Mass (kg)	=	51.36
Ion Thruster Thrust (mN)	=	129.00
Ion Thruster Power (kw)	=	3.06
Ion Thruster Fuel Tank Mass (kg)	=	12.00
Ion Thruster Specific Impulse (sec)	=	2900.00
Ion Thruster Specific Mass (kg/kw)	=	10.00
Ion OTV Structural Mass (kg)	=	300.00
Number of Ion Thrusters (#)	=	20.00

Table 4.2 Satellite Traffic Models

Satellite Mission	A_{sat} (km)	e_{sat}	I_{sat} (deg)	Mass (kg)	Launch Frequency (#/YR)
Test Missions					
I	6900	0.05	45.0	20000	3.0
II	40000	0.00	0.0	20000	3.0
III	6500	0.75	100.0	20000	3.0
Hypothetical Operational Missions					
1	41000	0.0	0.0	2000	3.0
2	20000	0.0	0.0	500	0.5
3	6700	0.0	28.5	25000	0.5
4	65000	0.0	55.0	1500	4.0
5	25000	0.7	65.0	1500	0.5
6	12000	0.0	90.0	4500	3.0
7	6700	0.0	98.0	8000	5.0

minimized. In each case SUMT specified a particular inclination and altitude for the SOC, which was compared with predicted values for that case. Table 4.3 shows predicted and calculated values for all cases.

All of the actual results either corresponded to the predicted results, or would have had no constraints been present. As an example the five simplified cases with only one satellite test mission (see Table 4.3) are individually interpreted. (All of the predicted SOC radii are constrained within the 6500 to 7200 km envelope):

1. ETR Orbiter Fuel Minimization--In this case only the Orbiter fuel consumption is minimized. The predicted SOC Radius is as low as possible (6500 km) while inclination is as high as possible. The latter is a result of the Orbiter being easiest to maneuver when its mass is lowest. Since payload mass decreases with increasing inclination, the inclination is driven high subject to the payload mass being greater than zero. As anticipated, SUMT drove the altitude to 6500 km and the inclination to 115.6° (payload mass infinitesimally greater than zero). Because this problem is independent of the number of test missions considered the results are not repeated for the two and three satellite test missions listed in Table 4.3.

2. OTV Fuel Minimization--In this case only the OTV fuel consumption is minimized. Consequently, the predicted SOC inclination and radius are identical to the satellite test missions inclination and radius. As anticipated, SUMT drove the inclination to 45° and the radius as high as possible subject to the Orbiter fuel consumption being less than 10830 kg. The latter constraint was again infinitesimally small per the prediction.

3. SOC Fuel Minimization--The SOC orbit maintenance fuel consumption is again independent of the number of test missions considered and is therefore listed only once in Table 4.3. The predicted

Table 4.3 Satellite Traffic Test Models

Test Missions	Minimized Performance Index	Optimized SOC Orbit: Predicted SOC Incl (deg)	Predicted SOC Radius (km)	Actual SOC Incl (deg)	Actual SOC Radius (km)	Reason for Deviation
I	ORB Fuel	Very High	6500	115.6	6500	Payload Mass Constraint
	OTV Fuel	45	6900	45.0	6757	ORB Fuel Constraint
	SOC Fuel	28.5	7200	45.0	6757	ORB Fuel Constraint
	STS Fuel	45	6900	44.9	6757	ORB Fuel Constraint
	STS Launch	45	6900	44.7	6757	ORB Fuel Constraint
I,II	OTV Fuel	28.5-45	6900-7200	43.8	6756	ORB Fuel Constraint
	STS Fuel	28.5-45	6900-7200	36.2	6720	ORB Fuel Constraint
	STS Launch	28.5-45	6900-7200	28.5	6695	ORB Fuel Constraint
I,II,III	OTV Fuel	28.5-57	6500-7200	46.7	6758	
	STS Fuel	28.5-57	6500-7200	45.0	6696	
	STS Launch	28.5-57	6500-7200	34.6	6697	

SOC radius is as high above the atmosphere as possible (7200 km) while the inclination is as low as possible. The latter is due to the atmospheric rotation factor of Section 3.2 which results in slightly less drag at lower inclinations. Again, SUMT drove the inclination to its lowest possible value of 28.5° and the radius as high as the Orbiter fuel constraint would allow (an unconstrained problem was also run which drove the radius to the predicted 7200 km).

4. ETR Extended STS Fuel Minimization--In this case the Orbiter, OTV and SOC orbit maintenance fuel consumption are minimized simultaneously. Because of the massive amount of fuel required for the OTV to change inclinations, OTV fuel consumption is the dominant factor in the minimization problem. Consequently the predicted SOC inclination and radius will be very near, but not identical to the satellite test missions inclination and altitude. As anticipated, SUMT drives the inclination to somewhat less than the predicted 45° inclination, and the radius towards 6900 km. The actual radius was limited to 6757 km due to the Orbiter fuel constraint.

5. ETR Extended STS Launch Minimization--This problem involves all the same components as the fuel minimization problem above. However, due to the payload advantage of launching to lower inclinations this model will tend to drive the SOC inclination somewhat lower than the previous case. The radius will again be driven to the satellite test mission radius. As anticipated, both predictions were verified with the Orbiter fuel consumption again constraining the radius.

In addition to a single satellite test mission, two and three test missions were used simultaneously for data as depicted in Table 4.3. In both cases predictions can be made only within broad limits; nonetheless the results again validated the accuracy of the model.

The test runs of Table 4.3 summarize the validation methodology used, but were not the only criterion used to validate the model. In addition, numerous similar runs were accomplished, as well as a vast number of hand calculations on every component of the model. In summary, the derived models appear to be extremely accurate although an independent verification by other investigators is desirable.

4.2 Models I and II--Fuel & Launch Minimization Solutions

To analyze each model several different scenarios were compared. Scenario A contains one SOC supplied by Shuttle launches from either the ETR or WTR, and servicing all seven operational missions in the traffic model of Table 4.2 Scenario B contains two SOCs with the first supplied by ETR and the second by WTR Shuttle launches. The ETR SOC services satellite missions 1 to 3 while the WTR SOC services missions 4 to 7. Scenario C is identical to B except the ETR SOC services missions 1 to 5 while the WTR SOC services missions 6 to 7. Scenario D contains a total of three SOCs. The first services missions 1 to 3 and is supplied by ETR Shuttle launches. The second services missions 4 to 5 and is supplied by ETR or WTR launches. The last SOC services missions 6 to 7 and is supplied by WTR launches. This information is summarized in Tables 4.4a and 4.4b where the combined fuel consumption and the number of Shuttle launches were respectively minimized.

Both problem variables (SOC inclination and radius), fuel mass, number of Shuttle launches and Orbiter payload mass are shown for each run of Tables 4.4a and 4.4b. The total minimum fuel consumption is then calculated for each scenario of Table 4.4a. Similarly, the total minimum number of Shuttle launches is calculated in Table 4.4b. All of the runs were made with the standard parameters of Table 4.1.

Table 4.4a Model I Fuel Minimization Scenarios

SOC Scen-ario	SOC#/ Satellite Missions Serviced	Launch Range	Optimized Values: SOC Incl (deg)	SOC Radius (km)	Payload Mass (kg/msn)	Fuel Mass (kg/yr)	STS Launches- (#/yr)	Minimum Total Fuel Mass (kg/yr)
A	SOC #1/1-7	ETR	57.00	6669.56	14823	1009048	48.14	1009048
		WTR	69.16	6644.87	11604	1125295	54.57	
B	SOC #1/1-3	ETR	28.50	6729.09	19780	135334	5.88	790297
	SOC #2/4-7	WTR	80.45	6654.96	7998	654963	39.05	
C	SOC #1/1-5	ETR	28.50	6712.44	20257	269021	10.55	694234
	SOC #2/6-7	WTR	85.65	6659.81	6333	425213	29.06	
D	SOC #1/1-3	ETR	28.50	6729.09	19780	135334	5.88	710562
	SOC #2/4-5	ETR	38.76	6728.49	17795	150015	6.33	
		WTR	66.97	6642.99	12295	343109	15.99	
	SOC #3/6-7	WTR	85.65	6659.81	6333	425213	29.06	

Table 4.4b Model II Launch Minimization Scenarios

SOC Scen-ario	SOC#/ Satellite Missions Serviced	Launch Range	Optimized Values: SOC Incl (deg)	SOC Radius (km)	Payload Mass to (kg/msn)	Fuel Mass (kg/yr)	STS Laun ches (#/yr)	Minimum Total STS Launches (#/yr)
A	SOC #1/1-7	ETR	57.00	6669.83	14825	1001380	47.70	47.70
		WTR	60.00	6637.24	14457	1193045	51.09	
B	SOC #1/1-3	ETR	28.50	6729.12	19779	134021	5.75	42.10
	SOC #2/4-7	WTR	71.15	6646.60	10973	712202	36.35	
C	SOC #1/1-5	ETR	28.50	6711.84	20274	267813	10.43	37.82
	SOC #2/6-7	WTR	78.07	6652.78	8762	463129	27.39	
D	SOC #1/1-3	ETR	28.50	6729.12	19779	134021	5.75	39.12
	SOC #2/4-5	ETR	28.50	6729.36	19772	152877	5.98	
		WTR	56.00	6634.10	15668	353084	14.33	
	SOC #3/6-7	WTR	78.07	6652.78	8762	463129	27.39	

Comparing the results of the two tables clearly demonstrates the similarities between the two performance indices. The primary difference between minimizing the number of launches instead of fuel consumption is that the SOC inclination is driven to a lower value as discussed in Section 4.1. Due to the similarities of the two models and the overwhelming cost of Shuttle launches (a recent General Accounting Office report cited $56 million per launch) the launch minimization model is used for all future calculations.

To analyze the sensitivity of the ETR Launch Minimization Model each of the standard parameters of Table 4.1 were varied. For the first eight the parameters were varied up and down by 50%. Due to their greater sensitivity the last two (Expended Mass at ETS and Shuttle Reference Mass) were only varied by 10%. Table 4.5 lists each parameter and its percent variation from standard. The optimized values listed include the SOC inclination, radius, combined fuel mass and total number of Shuttle launches.

The most sensitive parameters are the OTV specific impulse, OTV mass, Orbiter specific impulse, expended mass at ETS and the Shuttle reference mass. Varying the atmospheric scale height also has a significant effect on the model. This is especially noteworthy since atmospheric density (and therefore scale height) varies drastically with solar activity. Parameters which appear to have a minor impact on the model include the ballistic coefficient, SOC

Table 4.5 Model II ETR Launch Minimization--Variation of Standard Parameters

Standard Parameter	Percent Variation from Standard	Optimized Values			
		SOC Incl (deg)	SOC Radius (km)	Fuel Mass (kg/yr)	STS Launches (#/yr)
Standard Values	None	57.00	6669.83	1001380	47.70
Ballistic Coefficient (B=.02)	-50	57.00	6650.23	963760	46.07
	+50	57.00	6680.91	1024796	48.71
Scale Height (H=30)	-50	57.00	6597.01	852247	41.23
	+50	57.00	6726.77	1182170	55.53
OTV Mass (M_{otv}=2270)	-50	57.00	6678.97	702058	34.72
	+50	57.00	6662.87	1296771	60.50
SOC Mass (M_{soc}=100000)	-50	57.00	6650.23	963760	46.07
	+50	57.00	6681.16	1024793	48.71
SOC Cargo Mass (MC_{soc}=20000)	-50	57.00	6670.32	995811	47.02
	+50	57.00	6669.16	1006939	48.37
OTV Specific Impulse (ISP_{otv}=455)	-50	57.00	6609.96	8972304	393.20
	+50	50.29	6687.64	525403	24.99

Table 4.5 Continued

Standard Parameter	Percent Variation from Standard	Optimized Values			
		SOC Incl (deg)	SOC Radius (km)	Fuel Mass (kg/yr)	STS Launches (#/yr)
Standard Values	None	57.00	6669.83	1001380	47.70
SOC Specific Impulse (ISP_{soc}=455)	-50	57.00	6689.24	1042084	49.46
	+50	57.00	6658.50	979921	46.73
ORB Specific Impulse (ISP_{orb}=313)	-50	45.58	6559.97	3898959	152.34
	+50	57.00	6687.89	824038	40.01
Expended Mass at ETS (M_{et}=38399)	-10	57.00	6675.95	929248	38.21
	+10	55.37	6661.90	1143975	63.07
Shuttle Reference Mass (M_r=88041)	-10	57.00	6685.64	837456	29.38
	+10	47.84	6643.46	1707510	107.24

Mass, annual SOC cargo mass and the specific impulse of the SOC motors used for stationkeeping.

Three other quantities worth varying are the two problem variables (inclination and radius) and the launch frequencies in the Satellite Traffic Model. Table 4.6 shows the impact on the Extended STS fuel consumption, Shuttle launches and Shuttle payload mass when the SOC inclination and radius are varied. Initially the SOC radius is left at its optimum value while the inclination is varied from 30° to 100°. The inclination is then set at its optimum value while the radius is varied from 6500 to 7100 km. Both runs are done using ETR scenario A. The results clearly indicate that the minimum number of Shuttle launches is highly sensitive to the SOC inclination and altitude. This sensitivity lends credibility to the concept of designing the SOC such that its inclination and altitude can be changed over time. For example an altitude increase may be desirable during peak solar activity while an altitude or inclination change may be needed as the Satellite Traffic Model grows.

Table 4.7 depicts optimized values for various satellite launch frequencies. The launch frequencies of Table 4.1 are varied up and down by 25% and 50%. The optimized values include SOC inclination, SOC radius, Extended STS fuel mass and the number of Shuttle launches. Again, the number of Shuttle launches required is especially sensitive to any variation of the Satellite Traffic Model, especially launch frequencies.

Table 4.6 Model II ETR Launch Minimization--
Variation of SOC Incination and Radius

Variables (SOC Inclination/ Radius)	Non-Optimized Values		
	Fuel Mass (kg)	STS Launches #	STS Payload Mass (kg)
30.00/6669.83	2295026	80.45	21204
40.00/6669.83	1586637	61.02	19168
50.00/6669.83	1168620	50.57	16729
60.00/6669.83	955601	47.57	13967
70.00/6669.83	905932	52.85	10956
80.00/6669.83	1035994	72.39	7774
90.00/6669.83	1544388	134.21	4498
100.00/6669.83	5094436	590.79	1203
57.00/6500.00	>10000000	589.99	19298
57.00/6600.00	1355087	63.03	16688
57.00/6700.00	1023965	48.68	14010
57.00/6800.00	1274548	59.54	11259
57.00/6900.00	1737370	79.60	8432
57.00/7000.00	2710211	121.77	5524
57.00/7100.00	6053206	266.67	2528

Table 4.7 Model II ETR Launch Minimization--Variation of Satellite Launch Frequencies

Satellite Traffic	Satellite Launch Frequencies (missions)							Optimized Values			
Model	1	2	3	4	5	6	7	SOC Incl (deg)	SOC Radius (km)	Fuel Mass (kg)	STS Launches #
Very Low (-50%)	1.5	.25	.25	2.0	.25	1.5	2.5	57.00	6688.40	527161	25.43
Low (-25%)	2.25	.375	.375	3.0	.375	2.25	3.75	57.00	6677.58	766304	36.65
Median (Standard)	3.0	.5	.5	4.0	.5	3.0	5.0	57.00	6669.83	1001380	47.70
High (+25%)	3.75	.625	.625	5.0	.625	3.75	6.25	57.00	6663.57	1233493	58.61
Very High (+50%)	4.5	.75	.75	6.0	.75	4.5	7.5	57.00	6658.77	1463279	69.43

4.3 Model III--Launch Minimization Solutions with OTV/Shuttle Rendezvous in LEO

Only the first three scenarios (A, B and C) were used to evaluate the utility of an OTV/Shuttle rendezvous in LEO. A previous study indicated that such a strategy would probably not be worthwhile (Ref 16, p. 1-5). In contrast, the results of Table 4.8 indicate that significant savings are realizable if the Shuttle traffic is sufficiently high.

Comparing Table 4.8 to Table 4.4b demonstrates several surprising results. For Scenario A the OTV/Shuttle rendezvous strategy reduces the required number of Shuttle launches by 20% (47.70 to 38.27). For Scenarios B and C the corresponding launch savings are 33% (42.10 to 28.32) and 38% (37.82 t0 23.30) respectively. In terms of payload mass delivered to the SOC, these figures roughy correspond to a 20% payload increase for ETR launches and a 10% increase for WTR launches.

Although the OTV/Shuttle Rendezvous strategy appears very promising, several mitigating factors do exist. The Shuttle cargo and crew traveling to the SOC after rendezvous would have to be placed in modular containers that the OTV could dock with. Such containers would have to be built and rated for manned flight. Another potential problem lies in the WTR MECO Mass calculations. Appendix A calculates only the MECO mass above 70° inclination. A third order equation specifying the MECO mass as a function of inclination is

Table 4.8 Model III Launch Minimization--
OTV/Shuttle LEO Rendezvous Scenarios

			Optimized Values						
SOC Scen-ario	SOC#/ Satellite Missions Serviced	Launch Range	SOC Incl (deg)	SOC Radius (km)	Rendez-vous Incl (deg)	Payload Mass to SOC (kg/msn)	Fuel Mass (kg/yr)	STS Laun ches (#/yr)	Minimum Total STS Launches (#/yr)
A	SOC #1/1-7	ETR	57.00	6739.20	56.82	17648	785989	38.27	38.27
		WTR	62.22	6743.19	62.02	15780	847550	38.37	
B	SOC #1/1-3	ETR	28.50	6774.95	28.50	24121	98141	4.56	28.32
	SOC #2/4-7	WTR	76.39	6765.29	76.08	11628	401099	23.79	
C	SOC #1/1-5	ETR	28.50	6795.44	28.50	24043	207031	8.41	23.30
	SOC #2/6-7	WTR	86.02	6781.35	85.57	8787	182365	14.89	

then derived by linear regression. Consequently, the data for 56° to 70° inclinations is somewhat suspect. Since one of the WTR launches of Table 4.8 is within this range it is also suspect. Finally, the extent of the savings will depend on the traffic model used. Traffic models which place the optimum SOC altitude in a lower Earth orbit are not as greatly influenced by the OTV/Shuttle rendezvous strategy as higher altitude SOCs.

Several of the parameters of Table 4.5 were again varied within Model III. The OTV mass, OTV specific impulse, Orbiter specific impulse and Shuttle reference mass are all varied up and down by 50% or 10% as indicated in Table 4.9. As before the OTV mass, OTV specific impulse and the Shuttle reference mass were all critical parameters that again had a major impact on the calculated number of Shuttle launches. Unlike the previous case, an increase in the Orbiter specific impulse resulted in only a marginal decrease in the number of Shuttle launches. This outcome was predictable since the Orbiter, being deployed to a lower altitude, doesn't consume as much propellant.

Table 4.9 Model III ETR Launch Minimization--
Variation of OTV/Shuttle Rendezvous Parameters

Standard Parameter	Percent Variation from Standard	Optimized Values			
		SOC INCL (deg)	SOC Radius (km)	Fuel Mass (kg/yr)	STS Launches (#/yr)
Standard Values	None	57.00	6739.20	785989	38.27
OTV Mass (M_{otv}=2270)	-50	57.00	6754.18	533531	27.34
	+50	57.00	6726.68	1039639	49.26
OTV Specific Impulse (ISP_{otv}=455)	-50	56.89	6566.75	9418258	411.84
	+50	55.32	6762.12	362555	19.51
ORB Specific Impulse (ISP_{orb}=313)	-50	57.00	6732.29	1114322	52.44
	+50	57.00	6737.77	713118	35.13
Shuttle Reference Mass (M_R=88041)	-10	57.00	6741.25	714643	25.50
	+10	53.13	6730.82	1067731	75.43

4.4 Model IV--Launch Minimization Solutions with an Ion-Propelled OTV

The use of an ion propelled OTV to deploy and retrieve satellites can drastically reduce the number of Shuttle launches required to service satellites within the Traffic Model. Indeed, Tables 4.5 and 4.9 clearly demonstrate that a 50% increase in the OTV specific impulse dramatically reduces the number of Shuttle launches. With an ion-propelled OTV specific impulse can easily be increased by 1000% and more. Consequently, vast savings in fuel and Shuttle launches are possible if the user is willing to accept much longer deployment times.

Table 4.10 lists optimized values for a variety of different specific impulses. The optimized values include the SOC inclination, SOC radius, total fuel consumption, number of Shuttle launches and the average mission duration when deploying satellites. The 2900 and 9000 second impulses were chosen since ion systems with those capabilities exist or are being investigated. Both are 30 cm mercury ion thrusters being developed by NASA (Ref 13, p. 62). The SOC stationkeeping thrusters were generally assigned the same specific impulse as the OTV thrusters. The rationale is that if such thrusters are available they might as well be used for SOC orbit maintenance and orbit changes.

Table 4.10 Model IV ETR Launch Minimization--Variation of OTV/SOC Specific Impulse

Specific Impulse (sec)		Optimized Values				
OTV	SOC	SOC Incl (deg)	SOC Radius (km)	Fuel Mass (kg/yr)	STS Launches (#/yr)	Avg OTV Time-of-flight (days/msn)
2900	2900	28.50	6659.74	176585	9.17	425
2900	455	28.50	6711.87	197603	9.87	423
5000	5000	28.50	6651.31	106172	6.83	362
9000	455	28.50	6724.09	93017	6.39	328
9000	9000	28.50	6640.26	71397	5.67	330
10000	10000	28.50	6637.42	67331	5.54	326
20000	20000	28.50	6620.30	49112	4.93	311
30000	30000	28.5	6609.14	42645	4.72	306

With the use of ion thrusters the required number of annual Shuttle launches drops drastically. As a rough guess it would probably require ten or more annual launches for the Shuttle to directly deploy the satellites in the Traffic Model. In the extreme cases where specific impulse is set at 20000 and 30000 seconds, the number of Shuttle launches is easily less than half that required for direct Shuttle insertion. All of these runs were accomplished with the OTV mass set at 2270 kg.

Although such an OTV mass is certainly achievable, it may be desirable to add additional ion thrusters that would increase the mass, but decrease the mission durations. To evaluate the more general case where the OTV mass increases with the number of ion thrusters required the use of Eq. 3.30:

$$M_{otv} = N(M_{thr} + M_{sp} \times P_{wr} + M_{ft}) + M_{str}$$

The parameters used in this equation were for a NASA 30 cm Mercury ion thruster which has been developed and is being refined (Ref 13, p. 62). The actual parameter values are listed in Table 4.1. Also in Table 4.1 is the structural mass (M_{str}), the number of ion thruster and the specific mass of the ion system. The latter is simply the mass of the power system and conditioning equipment required to generate a 1 Kw output. The value of 10 Kg/Kw reflects the current level of technology. The resulting OTV mass is 2179 Kg, slightly less than the previous case. For consistencies sake the SOC orbit maintenance thrusters are assumed to be the same as on the OTV with a specific impulse of 2900 sec.

Scenarios A, B and C were used to evaluate this new model with Table 4.11 summarizing the results. The ETR Scenario A required only 9.08 annual Shuttle launches to service the Satellite Traffic Model. Scenario C with one SOC inclined at 28.5° and the other at 56° required about 2.4 additional launches per year. However, it has the benefit of two operating stations (also the extra expense) and somewhat smaller mission durations when deploying polar orbiting satellites. Scenario B is nearly identical to C except the average OTV mission duration is 240 vs 347 days. The smaller mission duration is advantageous since the number of OTVs required to service the satellite Traffic Model is proportionally smaller.

As in section 4.3 several of the key parameters were again varied. Both the Shuttle reference mass and the OMS specific impulse were varied as before. However, the OTV mass and specific impulse were not varied directly. Instead, several of the parameters used to calculate OTV mass were varied up and down by 50%. Table 4.12 summarizes the results of the sensitivity analysis. As anticipated, the Shuttle reference mass and Orbiter specific impulse had a pronounced effect on the number of Shuttle launches.

The remaining ion engine parameters had a relatively minor impact on the number of Shuttle launches. However, they had a major impact on the average OTV mission durations.

Table 4.11 Model IV Launch Minimization--Ion Propelled OTV Scenarios

			Optimized Values						
SOC Scen-ario	SOC#/ Satellite Missions Serviced	Launch Range	SOC Incl (deg)	SOC Radius (km)	Payload Mass (kg/msn)	Fuel Mass (kg/yr)	STS Launches (#/yr)	Avg OTV Time-of Flight (days/msn)	Minimum Total STS Launches (#/yr)
A	SOC #1/1-7	ETR	28.50	6660.00	21749	173869	9.08	415	9.08
		WTR	56.00	6634.10	15668	201579	11.34	417	
B	SOC #1/1-3	ETR	28.50	6699.24	20634	31728	2.35	240	11.52
	SOC #2/4-7	WTR	56.00	6634.10	15668	162659	9.17		
C	SOC #1/1-5	ETR	28.50	6691.01	20869	48702	3.14	347	11.45
	SOC #2/6-7	WTR	56.00	6634.10	15668	146722	8.31		

Table 4.12 Model IV ETR Launch Minimization--
Variation of Ion Propelled OTV Parameters

Standard Parameter	Percent Variation from Standard	Optimized Values				
		SOC Incl (deg)	SOC Radius (km)	Fuel Mass (kg/yr)	STS Launches (#/yr)	Avg Time-of Flight (days/msn)
Standard Values	ISP_{otv}=2900 ISP_{soc}=2900 M_{otv}=2179	28.50	6660.00	173869	9.08	415
Shuttle Reference Mass (M_r=88041)	-10	34.32	6672.01	140788	6.36	407
	+10	28.50	6643.35	230157	15.50	415
ORB Specific Impulse (ISP_{orb}=313)	-50	28.50	6656.73	571421	22.32	419
	+50	28.50	6675.97	142322	8.03	413
Ion Engine Thrust (T=0.1290)	-50	28.50	6659.92	173869	9.08	829
	+50	28.50	6659.92	173869	9.08	276
Number of Ion Thrusters (N=20)	-50	28.50	6662.93	145701	8.15	622
	+50	28.50	6657.31	201935	10.02	345

Table 4.12 (Cont.)

Standard Parameter	Percent Variation from Standard	Optimized Values				
		SOC Incl (deg)	SOC Radius (km)	Fuel Mass (kg/yr)	STS Launches (#/yr)	Avg Time-of Flight (days/msn)
Ion Thruster Mass (M_{thr}=51.36)	-50	28.50	6661.76	158485	8.57	358
	+50	28.50	6658.46	189222	9.60	471
Ion Thruster Power (P_{wr}=3.06)	-50	28.50	6659.68	164718	8.78	381
	+50	28.50	6659.04	183020	9.39	448
Specific Mass (M_{sp}=10)	-50	28.50	6659.68	164718	8.78	381
	+50	28.50	6659.04	183020	9.39	448

The ion engine thrust was by far the most significant parameter. A 50% increase in thrust caused the average mission duration to decrease from 415 to 276 days. A 50% variation in the number of ion thrusters, thruster mass, thruster power and the specific mass had a smaller, but still significant impact on the mission durations. The respective average durations were reduced to 346, 358, 381 and 381 days.

Although the OTV specific impulse was not varied in Table 4.12, the runs of Table 4.10 adequately measure the impact on Shuttle launches and mission durations. Both are significantly reduced. For example, varying the specific impulse from 2900 to 5000 seconds reduced the number of annual launches from 9.17 to 6.83 and the mission duration from 425 to 362 days.

4.5 Model V--Launch Minimization Solutions with Chemical OTV/STS Rendezvous in LEO and Ion OTV for Satellite Deployment

The final model minimized with SUMT is a combination of Models III and IV. A chemically propelled OTV is used to rendezvous with the Shuttle and retrieve modularized Shuttle payloads. The rendezvous orbit has an altitude equivalent to the ballistic Shuttle apogee after MECO (160 km). Consequently, only one Shuttle OMS burn is required to achieve orbit and one to de-orbit. The rendezvous inclination is set to the same value as the SOC inclination. This simplification is justified by the Model III results illustrated in Table 4.8. In that case the SOC and rendezvous inclinations were separate variables which the optimization procedure drove to nearly identical values.

Another fleet of ion-propelled OTVs is used to deploy the satellites in the traffic model. Although the ion-propelled OTV is much more fuel efficient than its chemical counterpart, it probably could not be safely used for a LEO Shuttle rendezvous. Atmospheric drag at lower altitudes may well be too great for an ion thrust system to overcome, especially during peak solar activity. Further, a chemically propelled OTV would probably be required for all manned missions. The ion system is too slow for either a manned rendezvous with the Shuttle in LEO or any other vehicle (possibly to repair a satellite).

Another noteworthy feature of this model is the quantity of Orbiter OMS fuel consumed. Even when deployed to such a low altitude the Orbiter fuel consumption is over 4900 Kg for ETR launches (over 8400 Kg for WTR), still a significant fraction of the 10830 Kg fuel tank capacity. It is probable that OMS fuel consumption could be significantly reduced by using less conservative ascent and de-orbit ΔVs, and by altering the standard MECO conditions to better utilize residual fuel within the External Tank. Appendix A delineates the crude mission planning equations used to calculate ascent and de-orbit ΔVs. The ETR ascent equation gives a ΔV roughly 10% higher than the actual requirement while the deorbit equation appears even more conservative. Tailoring these equations would reduce fuel consumption slightly while launching to different standard MECO conditions may result in dramatic fuel savings. Both options should be further evaluated in the light of data from future operational Shuttle launches.

Scenarios A, B and C were again used to evaluate Model V. Table 4.13 summarizes the results. The ETR Scenario A required 7.8 annual shuttle launches, a 14% reduction from Model IV. Scenario B required 9.11 and Scenario C required 9.08 annual launches, both down 21% from Model IV. For Scernarios A, B and C the average OTV mission TOF is 411, 243 and 347 days respectively. Scenario B is again significantly faster than the other two. However, at $56 million per launch scenario B is also somewhat more

Table 4.13 Model V Launch Minimization--Ion Propelled OTV and Shuttle Rendezvous Scenarios

SOC Scen-ario	SOC#/ Satellite Missions Serviced	Launch Range	Optimized Values						Total Minimum STS Launches (#/yr)
			SOC Incl (deg)	SOC Radius (km)	Payload Mass (kg/msn)	Fuel Mass (kg/yr)	STS Launches (#/yr)	Avg OTV TOF (days/msn)	
A	SOC #1/1-7	ETR	30.00	6735.80	24202	134792	7.80	411	7.80
		WTR	56.00	6725.38	17552	142589	9.12	414	
B	SOC #1/1-3	ETR	29.00	6826.95	24030	19806	1.94	243	9.11
	SOC #2/4-7	WTR	56.00	6732.33	17532	109801	7.17		
C	SOC #1/1-5	ETR	29.00	6823.42	24043	33409	2.62	347	9.08
	SOC #2/6-7	WTR	56.00	6805.80	18102	97781	6.46		

expensive to operate, around $73 million in annual launch costs. Part of this expense could be recouped if the 56° inclined SOC were supplied by ETR Shuttle launches instead of the Model's WTR launches. The ETR launches would have a significantly greater payload capability than their WTR counterparts.

4.6 Model VI--Model V Launch Minimization Solutions versus Average OTV Flight Times

From the perspective of reducing launch costs the Model V results of the last section appear very promising. Another equally important performance parameter which must be considered is the ion propelled OTV flight times. Long flight times to the satellite's mission orbit have an adverse impact on both functional reliability and operational utility. Consequently, from an operational perspective it would be ideal if both the flight time and number of Shuttle launches could be minimized. Unfortunately, to a great extent there is a quid pro quo trade off between the two performance indices. Flight times can be reduced by adding ion thrusters to the OTV, but the increased OTV and fuel mass requirements eventually drives up the number of Shuttle launches.

Implementation of a vector optimization process defines the exact trade off between the two indices. Figure 4.1 depicts the efficient frontier on which the Extended STS should be operated. It was calculated using the standard parameters of Table 4.1 with one scenario A SOC servicing the entire Traffic Model of Table 4.2. Each point on the curve has associated with it an optimal SOC altitude, inclination and number of ion thrusters on the OTV. The hyperbolic configuration demonstrates that up to the "knee"

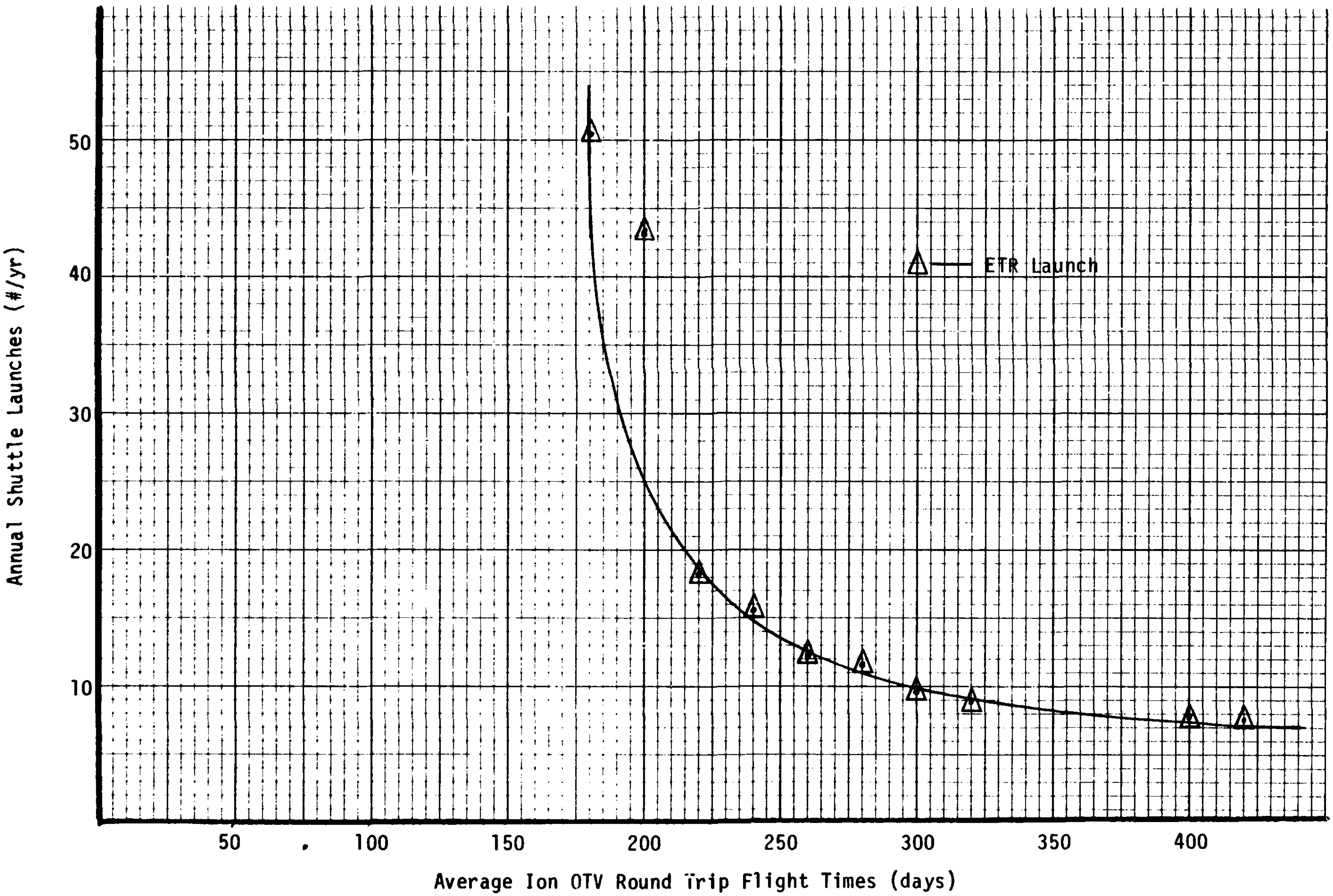

Fig. 4.1 Annual Scenario A Launches vs OTV TOF for Standard Parameters

of the curve average OTV flight times can be dramatically reduced without substantially increasing Shuttle launches. Below the knee annual Shuttle launch requirements increase exponentially. This flight time reduction is primarily due to a steady increase in the number of ion thrusters on the OTV. The exponential increase in Shuttle launches for lower flight times is a function of increasing OTV mass and fuel consumption. It corresponds to a surprisingly steep exponential increase in fuel consumption which may be partially due to operating the ion engines at a less than optimal exhaust velocity. For low thrust systems the maximum payload ratio for a given ΔV is always associated with a particular exhaust velocity (which corresponds to specific impulse). Any variation from the optimal exhaust velocity results in an exponential degradation of the payload ratio. Consequently, each mission in the Satellite Traffic Model has an optimal OTV specific impulse associated with it. Individually adjusting the ion engine thrust for each mission may allow the user to further reduce annual Shuttle launches or even deployment times.

Although better modeling may provide a refined efficient operating frontier, Fig. 4.1 is adequate for the purposes of this study. Indeed, its major drawback is that it is probably too conservative. To eliminate some of the conservatism the standard parameters and Traffic Model of Tables 4.1 and 4.2 were reviewed and assigned more realistic values where appropriate. Table 4.14 depicts the changes in

Table 4.14 Variations of Standard Parameters for Three Levels of Technology

Parameter	New Parameter Value		
	Level I ~ current	Level II ~ 1990	Level III ~ 2000
M_{soc}	Standard	Same	200000 kg
M_c	Standard	Same	26250 kg
M_r	85000 kg	Same	80000 kg
M_{thr}	Standard	Same	40 kg (-20%)
P_{wr}	Standard	6.862 Kw	10 Kw (+50%)
Thrust	Standard	298 mN	500 mN (+50%)
M_{sp}	Standard	5 Kg/Kw	1 Kg/Kw
Ion ISP_{otv}	Standard	3448 sec	5000 sec (+50%)
F_{sat}	Low Traffic Model	Same	Same

nine parameters for three different levels of technology. The first level is currently achievable and varies only the Shuttle reference mass and Traffic Model. The former should be easy to achieve by fine tuning the STS flight profile and mass configuration assumptions in Tables 3.1 and 3.2. The latter launch frequencies were reduced by 25% (see the Low Traffic Model of Table 4.7) to bring the number of annual Shuttle launches in line with more realistic projections of military traffic.

Level II technology incorporates only a slight upgrading of the 30 cm Hg ion engine. The new parameters were measured in NASA Lewis Research Center experiments (Ref. 17, Table 3), and can very probably be achieved in the 1990 timeframe. The projected specific mass of 5 Kg/Kw may be slightly optimistic, but it does appear to be achievable in the near term (Ref. 18). The last technology level is a projection based on current trends in ion engine research. Reducing thruster mass and specific mass are both high priority items. Ion engine thrust, power requirements and specific impulse are essentially linearly related over a given operating regime (Ref. 19, p 5-90). Consequently, these parameters are accordingly varied in Table 4.14. The Shuttle reference mass and specific mass are again reduced. The former increases the modeled Shuttle payload mass, and the introduction of light weight filament wound SRM casings will essentially accomplish the same. Again, the projected specific mass may be somewhat optimistic, but all of the projected parameters are realistic estimates for the 2000 timeframe.

Applying vector optimizaton to the three technology levels yields a consistent reduction in annual Shuttle launches and OTV flight times. Figure 4.2 graphically illustrates the improvement for all three levels with one SOC servicing the entire Low Traffic Model (scenario A). The three curves are depicted for ETR Shuttle luanches while the correspnding WTR Shuttle launch curve is also shown for Level I technology. The WTR supplied SOC is marginally less efficient than its ETR counterpart. However, the lack of accurate MECO mass data between 56° and 70° casts some doubt on the accuracy of this curve (the optimized SOC inclinations are in this region). In all probability it should be shifted upward somewhat, thus increasing annual Shuttle traffic and reflecting the decreased Shuttle payload capability of WTR launches.

In an attempt to further reduce OTV flight times, Scenario B with two SOCs was analysed for Level I technology. The first SOC services satellite missions 1 to 3 while the second services missions 4 to 7. Because the first three missions are all below 28.5° and the last four above 55° inclinations, the variable SOC inclinations were logically set at 28.5° and 57.0° respectively. These are the minimum and maximum inclinations accessible by ETR Shuttle launches, and specifying them as constants greatly reduced the SUMT optimization program convergence time.

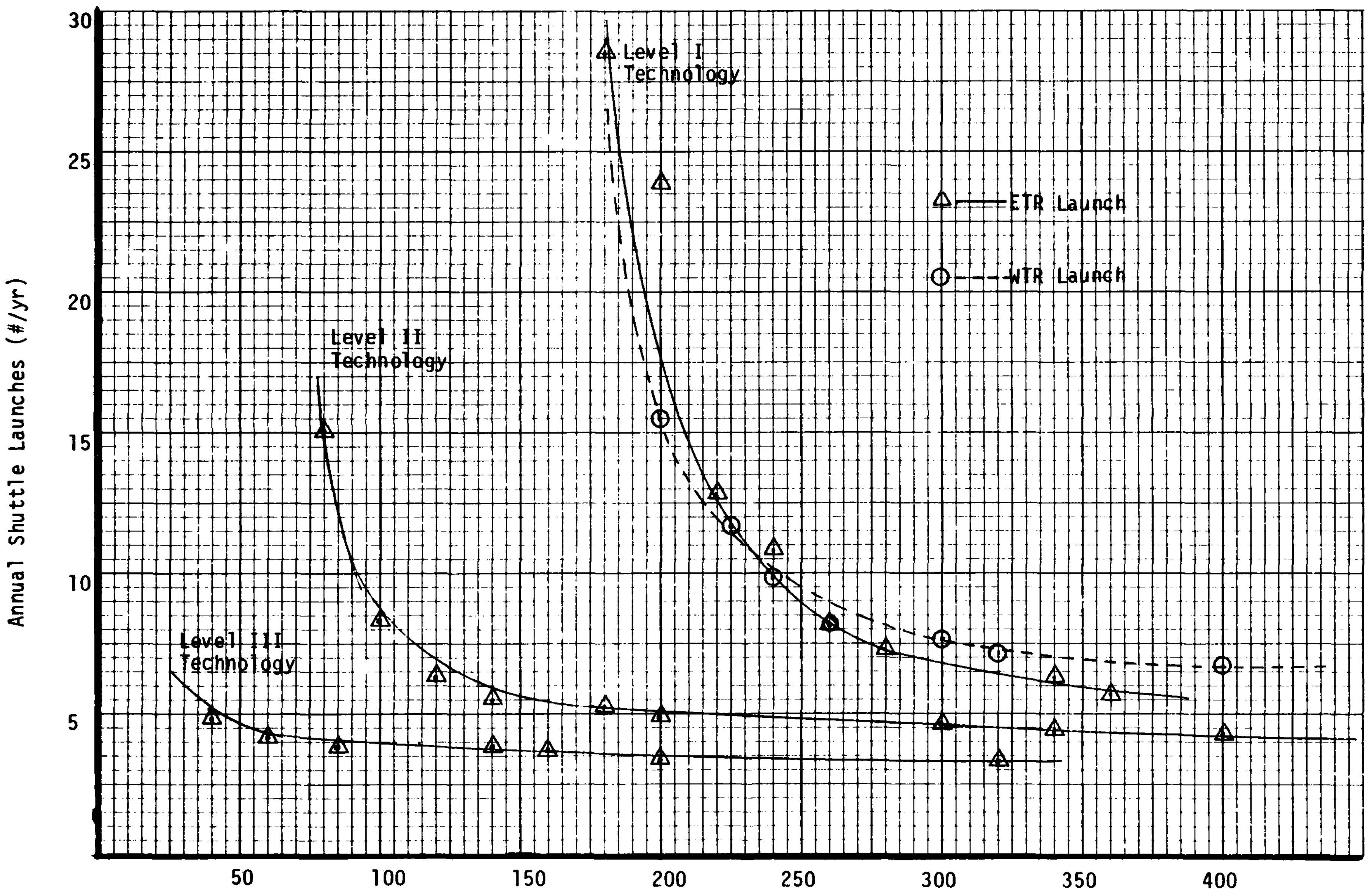

Fig. 4.2 Annual Scenario A Launches vs OTV TOF

Figures 4.3 and 4.4 illustrate the efficient operating frontiers for the dual SOC scenario. Both are supplied by ETR Shuttle launches although Fig. 4.4 again includes the corresponding WTR Shuttle resupply curve. The WTR curve reinserts the SOC inclination as an optimized variable and is again probably somewhat optimistic.

If the annual Shuttle launch rate and the average OTV mission duration are equally weighted performance indices, then the "best" point at which to operate the Extended STS is at the "knee" of the efficient operating frontier. Table 4.15 depicts several optimized values at the knee of each curve in Fig. 4.2 through 4.4. Besides the standard values depicted in previous tables, Table 4.15 includes the total number of ion propelled OTVs required to service the Traffic Model. This calculation assumes continuous utilization of every OTV. It should also be remembered that the average OTV flight times shown represent round trip times. The deployment times are of greater interest to military planners and are contained in the computer runs cataloged in Appendix D.

In summary, the dual or single SOC scenarios combined with the Level II technology available in the near term appears very attractive to the military user. Shuttle launch rates can probably be contained below current projections with reasonable satellite deployment times. The latter combined with the on-orbit spares philosophy already

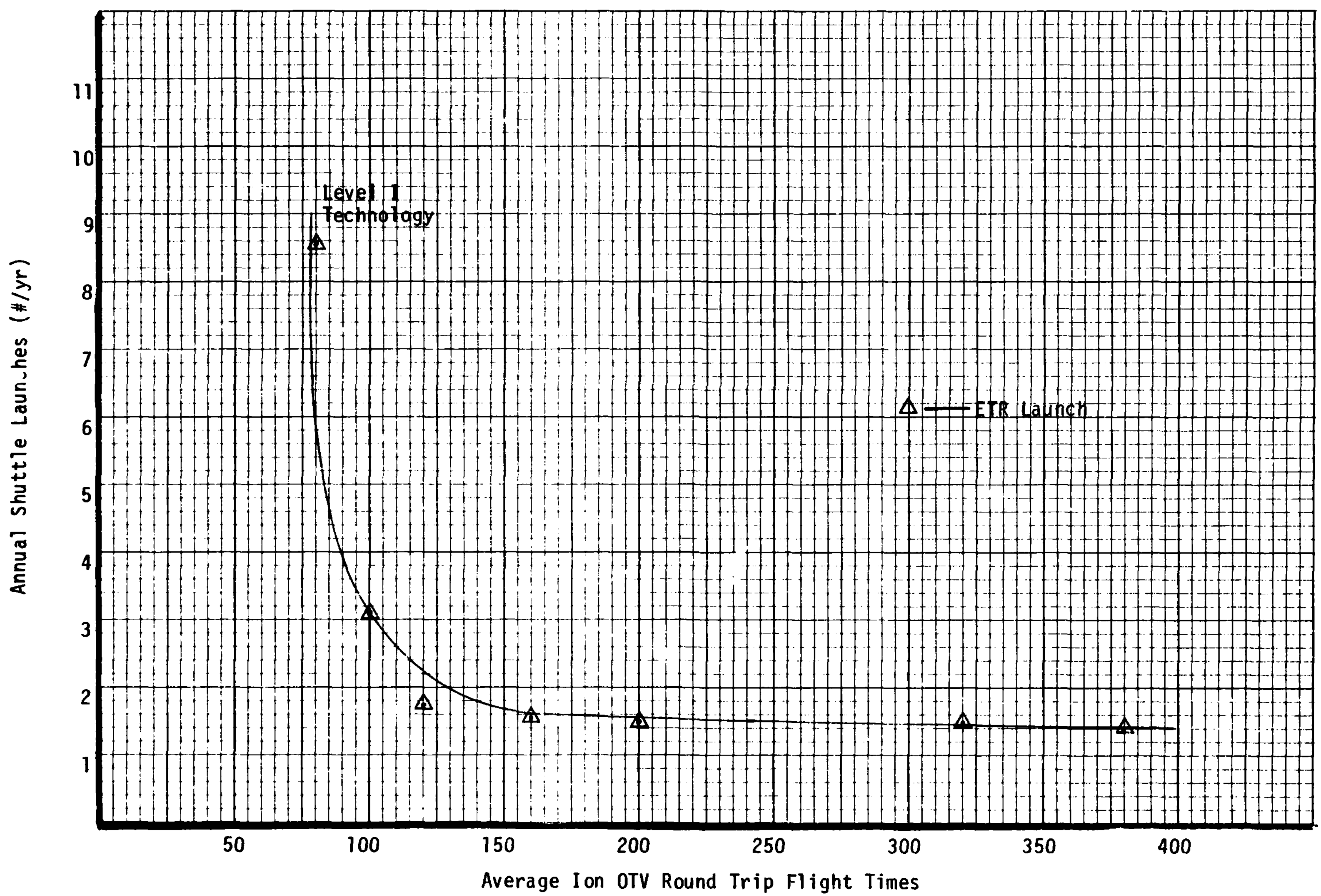

Fig. 4.3 Annual Scenario B Launches vs OTV TOF for Missions 1-3

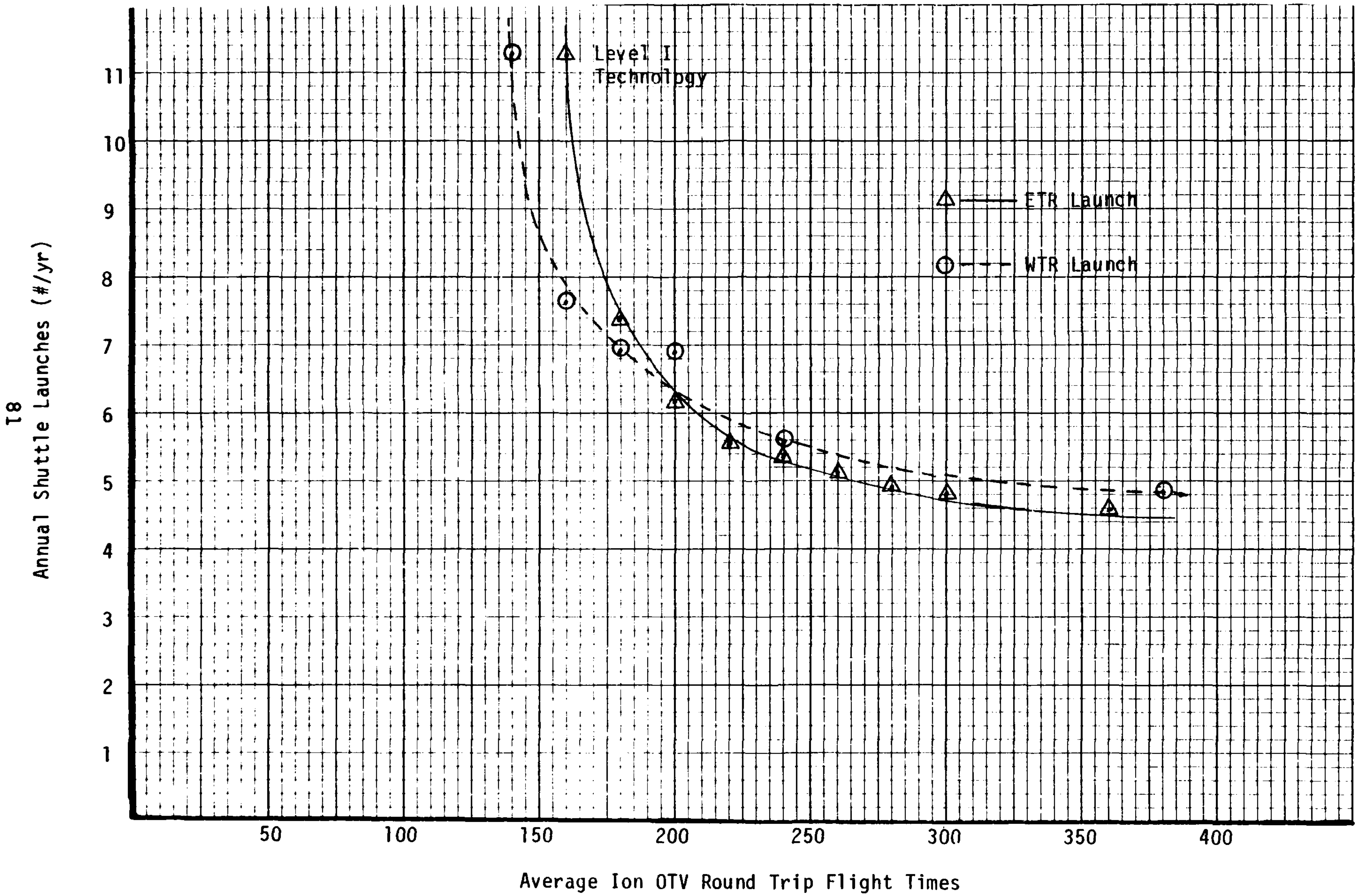

Fig. 4.4 Annual Scenario B Launches vs OTV TOF for Missions 4-7

Table 4.15 Model VI Launch Minimization -- Ion Propelled OTV

Scenarios from Efficient Operating Frontier of Figures 4.1-4.4

			Optimized Values							
Technology level	SOC Scenario	SOC#/ Satellites Missions Serviced	Launch Range	SOC Incl (deg)	SOC Radius (km)	No. of Ion Thrusters (#/OTV)	Avr. Ion OTV TOF (day/msn)	No. of Ion OTV (#)	STS Launches (#/yr)	Minimum Total STS Launches (#/yr)
I (current)	A	SOC #1/1-7	ETR	33.12	6661.22	67.74	260.00	4.98	8.16	8.16
			WTR	59.00	6708.07	57.36	260.00	4.98	8.17	
	B	SOC #1/1-3	ETR	28.50	6756.71	54.19	120.00	0.99	1.72	7.3
		SOC #2/4-7	ETR	57.00	6721.92	46.80	220.00	2.41	5.58	
			WTR	60.06	6670.23	31.43	240.00	2.63	5.56	
II (1990)	A	SOC #1/1-7	ETR	39.02	7087.77	43.59	120.00	2.30	6.31	6.31
III (2000)	A	SOC #1/1-7	ETR	41.00	7356.41	76.56	40.00	0.77	4.86	4.86

being pursued with military programs can satisfy the military requirement of rapid deployment.

5.0 Summary

The ability of a mathematical model to predict reality depends directly on the accuracy of the underlying assumptions. To avoid the faulty predictions of an overly optimistic model, most of the assumptions in Model's I through V were chosen to yield conservatively high estimates of annual Shuttle traffic. Conversely, Model VI eliminates several of the grosser assumptions and attempts to project the impact of evolving technology. A brief review of the impact key assumptions have on all six models follows:

1. Satellites in the Traffic Model are currently deployed individually. In many cases it will be much more efficient to deploy several satellites simultaneously.

2. Incorporation of satellite retrieval and repair missions requires additional OTV flights to service satellites in the Traffic Model. However, the number of new satellites deployed decreases proportionally.

3. A constant atmospheric scale height is used to calculate stationkeeping fuel consumption. The derived model gives reasonable results but needs to be verified by alternate methods.

4. Altitude and inclination changes are independently accomplished with the ion propelled OTV. Combining the maneuvers can result in significant fuel savings (Models IV through VI only).

5. The ion propelled OTV fuel mass calculation assumes 100% propellant utilization. For comparison the uprated 30 cm Hg engine of Table 4.14 has

a 94.3% propellant utilization rate (Models IV through VI only).

6. The calculated number of ion propelled OTVs represents a 100% utilization rate, in reality additional spare vehicles would be needed at the SOC (Model VI only).

In addition, two key assumptions eliminated by Model VI are contained in the first five models:

7. The Satellite Traffic Model postulated represents a high estimate of military traffic through the end of the century. The Low Traffic Model of Table 4.7 and Model VI requires fewer Shuttle launches to support, but compares favorably with more realistic projections of military traffic requirements.

8. The Orbiter mass configuration and flight profile assumptions of Tables 3.1 and 3.2 accurately specify MECO mass. However, several of the assumptions may be overly conservative, especially the Orbiter reference mass and the SRM inert mass. The reference mass can probably be substantially reduced by tailoring resupply missions while the use of filament wound SRM casings will likewise reduce the inert mass. Both have a dramatic impact on payload capacity.

Other assumptions made are delineated within the text of this study, but are not deemed significant enough to repeat.

The consistent conservatism exercised when making assumptions lends substantial confidence to the overall results of this study. Indeed, extrapolating the accuracy of the MECO mass calculations of Appendix A suggests that the overall Shuttle payload mass calculation is very likely within 10% and probably within 5% of the actual mass. Consequently, the calculated number of Shuttle launches throughout this study is probably also accurate to within 10%, or certainly calculable to that level by fine tuning the models and inputted data. In any case, the accuracy is more than sufficient for the gross requirements of this transportation study.

In addition to the model being accurate, the technological projections of Table 4.14 and Fig. 4.2 appear very reasonable. Projecting technology into the future is always risky and best avoided. However, for the sake of those involved in future planning it is also essential. The projection for 1990 timeframe technology represents a modest improvement in the Shuttle payload capability (still well below the nominal 65000 lb figure), and an uprating of current ion engine technology. The latter has already been demonstrated in the laboratory and is very probably feasible by 1990. Projecting technology to 2000 is more difficult. The projected Shuttle capability at this level is probably close to its maximum value without redesigning and refitting the vehicle. Projected ion engine technology is probably very reasonable with the possible exception of the specific mass which may be slightly optimistic. Overall, both the 1990 and 2000 technology projections appear imminently feasible with current funding of ion engine research.

Comparing the Extended STS to current Shuttle launch costs is complicated by the difficulty of estimating the number of STS launches required to deploy the postulated Satellite Traffic Model. The NASA STS Flight Assignment

Baseline projects that 42 of the first 60 operational Shuttle launches will be directly inserted to inclinations less than 57°. The total number of listed payloads is 106 thus requiring about 2.5 satellite payloads per ETR Shuttle launch (Ref. 20). Applying this figure to the first five missions of the Traffic Model in Table 4.2 yields at least three (3.4) annual launches to support those missions. The more massive satellites at polar inclinations will probably require one Shuttle launch per satellite. Adding the results gives a crude figure of eleven annual Shuttle launches to deploy the Satellite Traffic Model. The corresponding figure for the Low Traffic Model utilized in the Model VI results (Section 4.6) is eight annual Shuttle launches.

Comparing these figures to those derived by the various models of section 4.0 is enlightening. The SOC utilized in conjunction with the chemical OTV of Model II appears completely uneconomical except when used to deploy only satellite missions one to three. These satellites are deployed at inclinations ranging from equatorial to 28.5° and altitudes from Geosynchronous to low Earth orbit. Although Model II still requires a higher Shuttle launch rate (5.75 launches/yr) it must be remembered that this rate includes deployment and resupply of the SOC. In Model III the launch rate for missions one to three is reduced by about 21% (4.56 launches/yr) by having the OTV rendezvous with the Shuttle at a 160 km altitude. This compares even more favorably with direct Shuttle insertion of satellites. These two launch rates correspond to the Scenario B rates in Tables 4.4b and 4.8. Both are slightly conservative estimates of annual Shuttle launches due to a minor sign error in the MECO mass calculation (Models I to IV only--see Appendix C). The sign errors were corrected in the computer runs of Appendix D, but for consistencies sake are not incorporated in the results of Section 4.0. The corrected launch rates corresponding to the 5.75 and 4.56 values are 5.70 and 4.51 launches per year.

Model IV utilizes an ion propelled OTV to deploy satellites while Model V combines the chemical OTV/Shuttle rendezvous strategy of Model III with an ion propelled OTV for satellite deployment. The use of an ion propelled OTV drives the number of Shuttle launches to a value comparing favorably with direct Shuttle insertion of satellites. Indeed, if longer deployment times are acceptable Model V yields annual Shuttle traffic levels (7.80 launches/yr) that are significantly less than the 11 launches/yr estimated earlier. Model VI accomplishes a trade off analysis between satellite deployment times and the annual number of Shuttle launches in Model V. Figure 4.1 clearly shows the trade off between deployment times versus annual Shuttle traffic. By properly choosing the SOC inclination, altitude and OTV size, average deployment times can be dramatically reduced without substantially increasing Shuttle traffic.

Figures 4.2, 4.3 and 4.4 illustrate the same trade off analysis with lower more realistic estimates of satellite traffic. In addition, several ion engine and Shuttle flight parameters have been varied to eliminate some of the conservatism from the model. As previously estimated, direct orbital insertion of the Low Traffic Model would require about eight annual Shuttle launches. The corresponding efficient operating frontier for an Extended STS is illustrated in Fig. 4.2 for three technology levels. As before, annual Shuttle launches are less than eight with reasonable deployment times. The technology projections in the figure drastically reduce deployment times and slightly reduce annual Shuttle traffic. Figures 4.3 and 4.4 illustrate the efficient operating frontiers for two SOCs, one deploying missions one to three and the other missions four to seven. In this case the combined number of launches is slightly greater (still less than eight), but the deployment times are again drastically reduced even for current technology. The reduced deployment times possible with improved technology and/or the deployment of two SOCs, combined with an on-orbit spares philosophy, can satisfy the military requirement of rapid deployment.

The efficient operating frontier for an Extended STS supplied by WTR Shuttle launches is included in Fig. 4.2 and 4.4. Both show that ETR launches supplying a one or two SOC scenario are marginally more economical than WTR launches. However, this data is somewhat suspect due to the doubtful quality of the WTR MECO mass calculations between 56° and 70°, and the lack of a realistic Traffic Model. Nonetheless, if future more rigorous analysis substantiates these results the deployment of an Extended STS may eliminate the need for a WTR Shuttle launch site.

Although the Extended STS launch operations costs are less than those required to directly insert satellites into orbit with the Shuttle, other cost considerations also exist. Both development and orbital operations costs will contribute to the life cycle costs of the Extended STS. The latter can probably be accurately estimated while the former may not be as easy to quantify. However, by building a simple logistics depot, development costs can probably be contained at a reasonable level without any impact on the stations operational utility.

Again, although life cycle costs will be pivotal in any decision to deploy an Extended STS, there are additional considerations. The Extended STS offers a variety of inherent advantages (and a few disadvantages) over current STS operations. Among the advantages are:

1. The Shuttle can be loaded to 100% capacity for every launch. Current operations are well below this figure.

2. Utilizing the Shuttle as a simple cargo vessel will reduce the complexity of payload integration requirements.

3. The current upper stages required to deploy high altitude satellites will no longer be needed.

4. More extensive orbital test and validation operations will enhance satellite reliability and reduce early on-orbit failure rates. Ultimately, Factory-to-Orbit testing may significantly reduce the cost of system level testing at the factory and launch base.

5. Cost effective retrieval, repair and servicing of operational satellites can extend satellite lifetimes.

6. Orbital satellite spares can be stored at the station or at a slightly different altitude. Satellites deployed at different altitudes are periodically accessible with a small ΔV, yet are geographically dispersed and thus less vulnerable to attack (see section 3.4).

7. An ABM or ASAT system can be similarly deployed and periodically serviced by the OTV.

8. The Extended STS reduces the annual number of Shuttle launches required by current STS operations and therefore significantly reduces costs.

9. The Extended STS will give the United States a manned presence in space and a platform for the future expansion of manned activities.

Disadvantages of the Extended STS include the development and orbital operations costs, increased operational complexity, the risk of transporting LOX and Hydrogen fuel into orbit, longer deployment times for the ion propelled OTV, and the station's lack of survivability. The latter consideration is often overstated since the Extended STS is at least as survivable as the launch site and considerably less prone to sabotage. Further, destruction of a SOC utilized as a logistics depot would not affect the short term viability of operational forces. Other advantages and disadvantages can probably be readily identified, but the above summarize the key considerations.

6.0 Conclusion

The current STS augmented by a SOC and OTV appears to offer many attractive advantages over current Shuttle operations. Such an Extended STS will allow the Shuttle to be utilized as a cargo vessel rather than as an orbital work platform. The Shuttle launched to the SOC can consistently be loaded to 100% of its capacity. Directly inserting payloads into orbit with the Shuttle potentially requires more launches than transporting all satellite traffic to the SOC and deploying each vehicle to its final orbit with an OTV. The resultant reduction of launch costs is one of three major elements in the Extended STS life cycle costs: development and orbital operations being the other two. Only the launch costs of the Extended STS were estimated in this study.

The use of both chemical and ion propelled OTVs were evaluated for use in the Extended STS. The chemically propelled OTV with a specific impulse of 455 seconds was uneconomical except for the limited mission of deploying satellites to inclinations below 28.5°. Without suffering a massive payload penalty the Shuttle is incapable of launching to inclinations below the 28.5° ETR latitude. Consequently, the extended STS has a natural advantage over direct Shuttle insertion of low inclination satellites. The results of Model II (Section 4.2) show that over a 16 year period the Extended STS requires 5.70 annual Shuttle launches to deploy a SOC, OTV and the three satellite missions in the Traffic Model with inclinations below 28.5°. Model III (Section 4.3) offers additional savings by rendezvousing the OTV with the Shuttle in low Earth orbit and returning the payload to the SOC. The calculated annual Shuttle traffic for that scenario was 4.51, a 21% savings. Both of these figures can be compared with a crude estimate of about 3.4 annual Shuttle launches (Section 5.0) for direct insertion of Shuttle payloads. Although the Extended STS with a chemically propelled OTV is marginally uneconomical for low inclination missions, the economy of scales possible by including civilian and foreign satellite traffic will further reduce costs. Recalling that the Extended STS provides a permanent manned presence in space and obviates the need for many expensive upper stages, Shuttle launch rates actually compare favorably with direct insertion of Shuttle payloads even with the Satellite Traffic Model used in this study.

The OTV specific impulse is the most sensitive parameter in the evaluated Shuttle launch minimization models. A 50% increase in the Model III OTV specific impulse results in a 49% decrease in annual Shuttle launches with one SOC servicing all seven satellite missions in the Traffic Model (Table 4.9). Consequently, the use of ion engines on the OTV with their high specific impulses vastly reduces annual Shuttle traffi in t Extended STS. Use of existing 30 cm diameter mercury ion thrusters provides reasonable satellite deployment times which, when combined with the concept of orbital spares, can satisfy the military requirement of rapid deployment. Figure 4.2 shows the trade off between the average OTV mission duration and annual Shuttle launches for one SOC servicing the entire Satellite Traffic Model. Using the Low Traffic Model and deploying the satellites via direct Shuttle insertion without an Extended STS requires approximately 8 annual Shuttle launches. Using an Extended STS with 30 cm mercury ion engines mounted on the OTV requires 8.16 annual Shuttle launches per year with an average OTV mission duration of 260 days. Deploying two SOCs at 28.5° and 57.0° inclinations reduces annual Shuttle traffic to 7.3 launches with a 170 day average OTV mission duration. Alternatively, projecting the ion engine and Shuttle technology into the 1990 timeframe for a single SOC scenario reduces Shuttle traffic to 6.31 annual launches with a 120 day average OTV mission duration (Table 4.15). In all cases the annual Shuttle traffic can be further reduced if longer OTV mission durations are deemed acceptable.

Combining a dual SOC scenario with the uprated ion engine and Shuttle technology available by 1990 should further reduce both Shuttle traffic and the average OTV mission duration. Annual Shuttle traffic should be below five to six launches and the average OTV mission duration well below 100 days. Consequently, using the figure $56 million per Shuttle launch estimated in a recent General

Accounting Office report, an Extended STS may save as much as several hundred million dollars in annual Shuttle launch costs. Accomodating future missions is simulated by increasing the SOC and annual cargo mass. Annual Shuttle traffic is relatively insensitive to variations in both parameters and only moderately increases launch costs.

The Extended STS composed of either a chemically or ion propelled OTV obviates the need for the current fleet of expensive upper stages, and provides an orbital platform for the expansion of manned operations in space. The launch and orbital operating costs of the system compare favorably and may be less than the cost of current Shuttle operations. Perhaps more important from a military perspective, the SOC can be utilized as a logistics depot from which the current satellite fleet can be serviced. Orbital test, repair and service operations at the SOC can enhance the reliability and increase the lifetime of satellites in orbit. The evolutionary development of a Factory-To-Orbit test concept may eventually reduce expensive factory and launch base testing. Combined with new satellite designs entailing modular maintenance, system self testing and simplified procedural testing military personnel in orbit may one day be able to routinely salvage billions of dollars in satellite hardware.

The models developed in this study have several applications. For the strategic planner they offer a means of quantifying the cost of various Extended STS configurations. With a few refinements and a more rigorous analysis they could be very useful in the current national debate over whether to deploy a SOC. For the engineer they offer considerable insight into how to efficiently design an Extended STS. They are especially useful to the ion engine designer trying to build an efficient and effective OTV. As an engineering tool the SUMT program turned out to be an efficient numerical optimization routine for this type of problem. Finally, as an academic exercise they have radically altered my own views on how to best exploit the military and civilian potential of the space environment.

7.0 Research and National Space Policy Recommendations

Although this thesis provides a framework for evaluating the Extended STS, much more research is needed. The Satellite Traffic Model needs to be refined, and more realistic military and civilian satellite traffic incorporated. In addition, the scenarios and assumptions of Sections 3.0 and 4.0 need to be fine tuned by knowledgable personnel involved in STS operations and future planning. Finally, a means of quantifying the development and orbital operations costs needs to be established and linked to the overall life cycle costs of the Extended STS. Included within this evaluation would be some means of quantifying the specified advantages of an Extended STS, especially the savings due to satellite retrieval, repair and service. Additionally, the impact of accomplishing future missions such as deploying and maintaining an ABM or ASAT system needs to be incorporated into the models, possibly utilizing some of the ideas of Section 3.6.2.

With regards to a national space policy the results of this research tentatively suggests that the military and civilian utility of an Extended STS is best pursued by an evolutionary approach. Four operational phases that fall out of this study are:

1. Deploy a free-flying reusable chemical OTV to a 28.5° inclination. The vehicle would be used to deploy low inclination and especially Geosynchronous satellites. Deployment of such satellites eliminates the need for mission peculiar upper stages and will prove the basic concept of deploying satellites via a reusable OTV.

2. Add a low inclination SOC to the constellation as soon as possible. The SOC will prove the concept of doing logistics depot work in orbit.

3. Deploy an ion propelled OTV to reduce fuel costs and increase the number of satellite missions serviced. In addition, modify the Chemical OTV for manned missions and retrieval of low Earth orbit Shuttle payloads.

4. Incorporate satellite retrieval, service, repair and refurbishment operations. Consider deploying an additional SOC at higher inclinations to reduce ion propelled OTV deployment times. Other operational missions such as Satellite Storage or an ABM/ASAT system can also be implemented during this phase.

Although these recommendations are somewhat subjective, based on this research they appear to offer a reasonable balance between designing a cost effective and an operationally effective Extended STS.

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Appendix A

General STS Information

Modeling the Shuttle payload mass as a function of inclination and altitude was difficult due to a paucity of information about Shuttle flight characteristics. Acquisition of the NASA document "Ascent Performance and Payload Estimation Technique for Nominally Shaped Operational Missions" (Ref 5) was an invaluable aid. The document allowed Shuttle MECO masses to be calculated for particular Shuttle configurations. Tables 3.1 and 3.2 delineate the mass configuration and assumptions made in calculating the Shuttle MECO mass. These masses were tabulated and modeled as a function of inclination with a third order regression analysis. The resulting equations (Eqs. 3.4) are depicted for both the ETR and WTR.

As mentioned in section 3.1 the error associated with these MECO mass calculations is small. Computer runs A-1 and A-2 list all of the "actual" calculated MECO masses as well as the corresponding "predicted" masses from Eqs. 3.4. Reference 5 estimates that the actual masses are accurate to within 136 Kg (300 lbs) for ETR and 227 Kg (500 lbs) for WTR launches. The correlation coefficients for Eqs 3.4 are greater than .99999 for both the ETR and WTR functions, while the standard deviations are 4.1 and 6.1 Kg respectively. Consequently, if the NASA error estimates are accurate, Eqs. 3.4 should be able to predict MECO mass to within the maximum 3-sigma error of 148 Kg for ETR and 245 Kg for WTR launches.

The MECO mass calculation presumes that the shuttle is launched to a set of standard MECO conditions. For the ETR the conditions are an altitude of 57 NM, a flight path angle of 0.65 degrees and an inertial velocity of 25680 fps. The WTR conditions are identical except the inertial velocity is 25374 fps. Although these conditions could be varied for a particular mission, the majority of planned launches will be targeted to achieve standard conditions at MECO.

With the MECO mass known, the only other variables needed to calculate payload mass are the Shuttle reference mass and the OMS fuel consumption. The former depends on the Orbiter mass configuration detailed in Table 3.1 while the latter can be calculated from the velocity change required to achieve a given altitude. This velocity change is estimated by NASA mission planners (Ref 6) using the equations:

$$\Delta VA_{etr} = \begin{cases} 3.55\ HGT - 137\ \text{fps} & \text{for } HGT < 175\ \text{NM} \\ 3.44\ HGT - 117\ \text{fps} & \text{for } HGT > 175\ \text{NM} \\ \Delta VA_{wtr} - 281\ \text{fps} & \end{cases}$$

(Eqs. A-1)

$$\Delta VD = \begin{cases} 276\ \text{fps} & \text{for } HGT < 130\ \text{NM} \\ .72\ HGT + 183\ \text{fps} & \text{for } 130 < HGT < 170\ \text{NM} \\ 1.3\ HGT + 84\ \text{fps} & \text{for } 170 < HGT < 230 \\ 1.46\ HGT + 48\ \text{fps} & \text{for } HGT > 230 \end{cases}$$

where ΔVA_{etr}, ΔVA_{wtr} and ΔVD represent the velocities required to ascend to a given altitude (HGT) and then to deorbit. The equations include a velocity reserve which equates to an OMS propellant reserve.

The altitude of Eqs. A-1 can easily be converted to distance from the Earths center (radius). A second order linear regression can then be run on the radius and its corresponding velocity change. Computer runs A-3 and A-4 list the "actual" and "predicted" radii and ΔVs (in MKS units). The corresponding equations for $\Delta VAetr$, ΔVA_{wtr} and ΔVD are listed in section 3.1 (Eqs. 3.5) as a function of radius. The correlation coefficients for ΔVA_{etr} and ΔVD are 0.99999 and 0.99636, while the standard deviations are 0.23649 and 3.61089 respectively.

With the MECO mass, ΔVA and ΔVD known, Eq. 3.8 can be applied to calculate the payload mass. Due to the accuracy of the initial MECO mass calculation the derived payload masses should also be very accurate. Indeed, because the estimates for Shuttle reference mass, ascent and deorbit ΔVs, and the RCS fuel consumption are somewhat conservative, it is very likely that the calculated payload mass is somewhat conservative. Better estimates of the above variables by more knowledgable individuals would allow for a more accurate determination of payload mass as a function of inclination and altitude.

Computer Run A-1 ETR MECO Mass Versus Inclination
Regression Analysis

Variable Name and Type:

Inclination = X => Independent variable
Mass = Y => Dependent variable

Third Order Regression Analysis Coefficients:

Zero degree coefficient = +159275.829
First degree coefficient = + 3.3575
Second degree coefficient = - 3.70994
Third degree coefficient = + 0.01339

Regression Analysis Parameters:

Variance of estimate = 16.84896
Standard error of estimate = 4.10475
Correlation coefficient = 0.99999
Degrees of freedom = 12

Table of Residuals:

	Actual 'X'	Actual 'Y'	Predicted 'Y'	Residual
1	28.4 deg	156688 kg	156685.561 kg	2.4388
2	30	156399	156399.083	-0.0825
3	32	156020	156022.987	-2.9866
4	34	155625	155627.493	-2.493
5	36	155212	155213.245	-1.2446
6	38	154782	154780.884	1.1163
7	40	154335	154331.053	3.9469
8	42	153867	153864.395	2.6046
9	44	153382	153381.553	0.4467
10	46	152882	152883.169	-1.1693
11	48	152368	152369.886	-1.886
12	50	151840	151842.346	-2.3461
13	52	151301	151301.192	-0.1923
14	54	150748	150747.067	0.9328
15	56	150182	150180.613	1.3868
16	58	149602	149602.473	-0.4731

Computer Run A-2 WTR MECO Mass Versus Inclination
Regression Analysis

Variable Name and Type:

Inclination = X => Independent variable
Mass = Y => Dependent variable

Third Order Regression Analysis Coefficients:

Zero degree coefficient = +164628.209
First degree coefficient = - 79.17494
Second degree coefficient = - 3.01734
Third degree coefficient = + 0.01256

Regression Analysis Parameters:

Variance of estimate = 36.63971
Standard error of estimate = 6.05307
Correlation coefficient = 0.99999
Degrees of freedom = 17

Table of Residuals:

	Actual 'X'	Actual 'Y'	Predicted 'Y'	Residual
1	70 deg	148620 kg	148609.145 kg	10.8553
2	72	147974	147973.791	0.2087
3	74	147330	147336.003	- 6.0032
4	76	146688	146696.383	- 8.3833
5	78	146047	146055.534	- 8.5345
6	80	145409	145414.060	- 5.0597
7	82	144771	144772.562	- 1.5618
8	84	144136	144131.644	4.3563
9	86	143503	143491.908	11.0917
10	88	142862	142853.958	8.0417
11	90	142224	142218.397	5.6031
12	92	141588	141585.827	2.1733
13	94	140957	140956.851	0.1491
14	96	140330	140332.072	- 2.0721
15	98	139708	139712.093	- 4.0933
16	100	139093	139097.517	- 4.5174
17	102	138484	138488.947	- 4.9473
18	104	137883	137886.986	- 3.9860
19	106	137292	137292.236	- 0.2361
20	108	136708	136705.301	2.6993

Computer Run A-3 ETR Shuttle Orbit Radius Versus
Ascent Characteristic Velocity
From MECO Regression Analysis

Variable Name and Type:

Shuttle Orbit Radius = X => Independent variable
Characteristic velocity = Y => Dependent variable

Second Order Regression Analysis Coefficients:

Zero degree coefficient = -4623.658232
First degree coefficient = + 0.8474467398
Second degree coefficient = - 0.00002023703587

Regression Analysis Parameters:

Variance of estimate = 0.05593
Standard error of estimate = 0.23649
Correlation coefficient = 0.99999
Degrees of freedom = 41

Table of Residuals:

	Actual 'X'	Actual 'Y'	Predicted 'Y'	Residual
1	6498 km	28.4 m/s	28.5620 m/s	-0.1620
2	6508	34.2	34.4044	-0.2044
3	6518	40.0	40.2428	-0.2428
4	6528	45.9	46.0072	-0.1772
5	6538	51.7	51.9075	-0.2075
6	6548	57.6	57.7337	-0.1337
7	6558	63.4	63.5559	-0.1559
8	6568	69.3	69.3741	-0.0741
9	6578	75.1	75.1882	-0.0882
10	6588	80.9	80.9983	-0.0983
11	6598	86.8	86.8043	-0.0043
12	6608	92.6	92.6062	-0.0062
13	6618	98.5	98.4042	0.0958
14	6628	104.3	104.1980	0.1020
15	6638	110.2	109.9878	0.2122
16	6648	116.0	115.7736	0.2264
17	6658	121.8	121.5553	0.2447
18	6668	127.7	127.3330	0.3670
19	6678	133.5	133.1067	0.3933
20	6698	145.2	144.6418	0.5582

Table of Residuals (Continued):

	Actual 'X'	Actual 'Y'	Predicted 'Y'	Residual
21	6718	156.8	156.1607	0.6393
22	6738	168.2	167.6635	0.5365
23	6758	179.5	179.1500	0.3500
24	6778	190.8	190.6204	0.1796
25	6798	202.1	202.0745	0.0255
26	6818	213.4	213.5125	-0.1125
27	6838	224.8	224.9343	-0.1343
28	6858	236.1	236.3399	-0.2399
29	6878	247.4	247.7293	-0.3293
30	6898	258.7	259.1025	-0.4025
31	6918	270.1	270.4596	-0.3596
32	6938	281.4	281.8004	-0.4004
33	6958	292.7	293.1251	-0.4251
34	6978	304.0	304.4335	-0.4335
35	6998	315.4	315.7258	-0.3258
36	7018	326.7	327.0019	-0.3019
37	7038	338.0	338.2618	-0.2618
38	7058	349.3	349.5055	-0.2055
39	7078	360.7	360.7330	-0.0330
40	7098	372.0	371.9443	0.0557
41	7118	383.3	383.1394	0.1606
42	7138	394.6	394.3183	0.2817
43	7158	405.9	405.4811	0.4189
44	7178	417.3	416.6277	0.6723

Computer Run A-4 ETR Shuttle Orbit Radius Versus
Deorbit Characteristic Velocity
Regression Analysis

Variable Name and Type:

Shuttle Orbit Radius = X => Independent variable
Characteristic velocity = Y => Dependent variable

Second Order Regression Analysis Coefficients:

Zero degree coefficient = +7994.436744
First degree coefficient = - 2.50173195
Second degree coefficient = + 0.0001974610171

Regression Analysis Parameters:

Variance of estimate = 13.03851
Standard error of estimate = 3.61089
Correlation coefficient = 0.99636
Degrees of freedom = 41

Table of Residuals:

	Actual 'X'	Actual 'Y'	Predicted 'Y'	Residual
1	6498 km	84.1 m/s	78.1085 m/s	5.9915
2	6508	84.1	78.7766	5.3234
3	6518	84.1	79.4841	4.6159
4	6528	84.1	80.2311	3.8689
5	6538	84.1	81.0177	3.0823
6	6548	84.1	81.8437	2.2563
7	6558	84.1	82.7092	1.3908
8	6568	84.1	83.6142	0.4858
9	6578	84.1	84.5587	-0.4587
10	6588	84.1	65.5427	-1.4427
11	6598	84.1	86.5661	-2.4661
12	6608	84.1	87.6291	-3.5291
13	6618	84.1	88.7316	-4.6316
14	6628	85.4	89.8735	-4.4735
15	6638	86.6	91.0550	-4.4550
16	6648	87.8	92.2759	-4.4759
17	6658	89.0	93.5363	-4.5363
18	6668	90.1	94.8363	-4.7363
19	6678	91.3	96.1757	-4.8757
20	6698	94.1	98.9730	-4.8730

Table of Residuals (Continued):

	Actual 'X'	Actual 'Y'	Predicted 'Y'	Residual
21	6718	98.3	101.9282	-3.6282
22	6738	102.6	105.0415	-2.4415
23	6758	106.9	108.3127	-1.4127
24	6778	111.2	111.7419	-0.5419
25	6798	115.5	115.3290	0.1710
26	6818	120.4	119.0741	1.3259
27	6838	125.2	122.9772	2.2228
28	6858	130.0	127.0383	2.9617
29	6878	134.8	131.2573	3.5427
30	6898	139.6	135.6343	3.9657
31	6918	144.4	140.1693	4.2307
32	6938	149.2	144.8622	4.3378
33	6958	154.0	149.7131	4.2869
34	6978	158.8	154.7219	4.0781
35	6998	163.6	159.8888	3.7112
36	7018	168.4	165.2136	3.1864
37	7038	173.2	170.6964	2.5036
38	7058	178.0	176.3371	1.6629
39	7078	182.8	182.1358	0.6642
40	7098	187.6	188.0925	-0.4925
41	7118	192.4	194.2071	-1.8071
42	7138	197.3	200.4798	-3.1798
43	7158	202.1	206.9103	-4.8103
44	7178	206.9	213.4989	-6.5989

APPENDIX B

Scale Height Modeled with Skylab Orbit Maintenance Data

The atmospheric model of section 3.2 is used to calculate the orbit maintenance fuel cost of maintaining the SOC at constant altitude. Fuel cost was calculated from the average SOC acceleration due to air drag. Acceleration, calculated by Eq. 3.11, is in turn a function of the SOC ballistic coefficient, inclination, radius and scale height. All of these parameters are known or can be accurately estimated.

Initially the scale height was modeled by linear regression. The mean COSPAR international Reference Atmosphere (CIRA) with the values of scale height averaged over the day/night cycle was used to derive scale height as a function of radius. Unfortunately, the curve fit was not very good, and when used in the SUMT minimization routine it gave unrealistically high estimates of fuel consumption. Early Skylab data was then used to estimate a realistic value for the scale height. To resolve the dilemma a constant value of scale height was decided on since it could be varied to give realistic estimates of fuel consumption.

Skylab was a large space station placed at an inclination of 50° and a radius of 6811 km (234NM altitude). Data from the mission was used to calculate a realistic value for the scale height. Figure B-1 depicts the Skylab ΔV maneuvers required for orbit maintenance through the first two manned flights. The five ΔV maneuvers accomplished during the 144 days of flight correspond to an average acceleration due to air drag of 1.8×10^{-7} m/sec^2. Alternatively, the three final maneuvers accomplished during the last 64 days correspond to an acceleration of 3.0×10^{-7} m/sec^2. In addition to estimating the Skylab acceleration due to air drag, mass and surface area figures were used to calculate a ballistic coefficient in the range .015 to .02 (C_dS/M).

The above figures were used in conjuction with Eq. 3.11 to calculate the scale height (H). Rearranging Eq. 3.11:

$$H = \frac{(R_o - R_{soc})}{\ln[(2A_{soc} x R_{soc})/(U x P_o x B x (.00175\ I_{soc} + .84004))]}$$

where,

R_o = 6498 km

P_o = 24.9 kg/km^3

U = 398601.2 km^3/sec^2

I_{soc} = 50^o

R_{soc} = 6811 km

$$(A_{soc}/B)min = 1.2 \times 10^{-5}\ kg/msec^2$$

$$(A_{soc}/B)max = 1.5 \times 10^{-5}\ kg/msec^2$$

The resulting values of scale height are 28.6 and 29.2 km. These values correspond to the average acceleration experienced by Skylab during its first five months in orbit. The specific value of scale height will vary over the day/night cycle, and even the average value varies with Solar activity. Nonetheless, the above values inserted into the atmospheric model of section 3.2 provide an average estimate of the Skylab orbit maintenance fuel consumption.

Consequently, a scale height of 30 km was chosen for use within the orbit maintenance fuel consumption model. Applied to the Skylab data, this figure of scale height results in a slightly conservative estimate of fuel consumption. Higher values of scale height would be even more conservative. Although not perfect, a constant scale height is adequate for the purposes of this study.

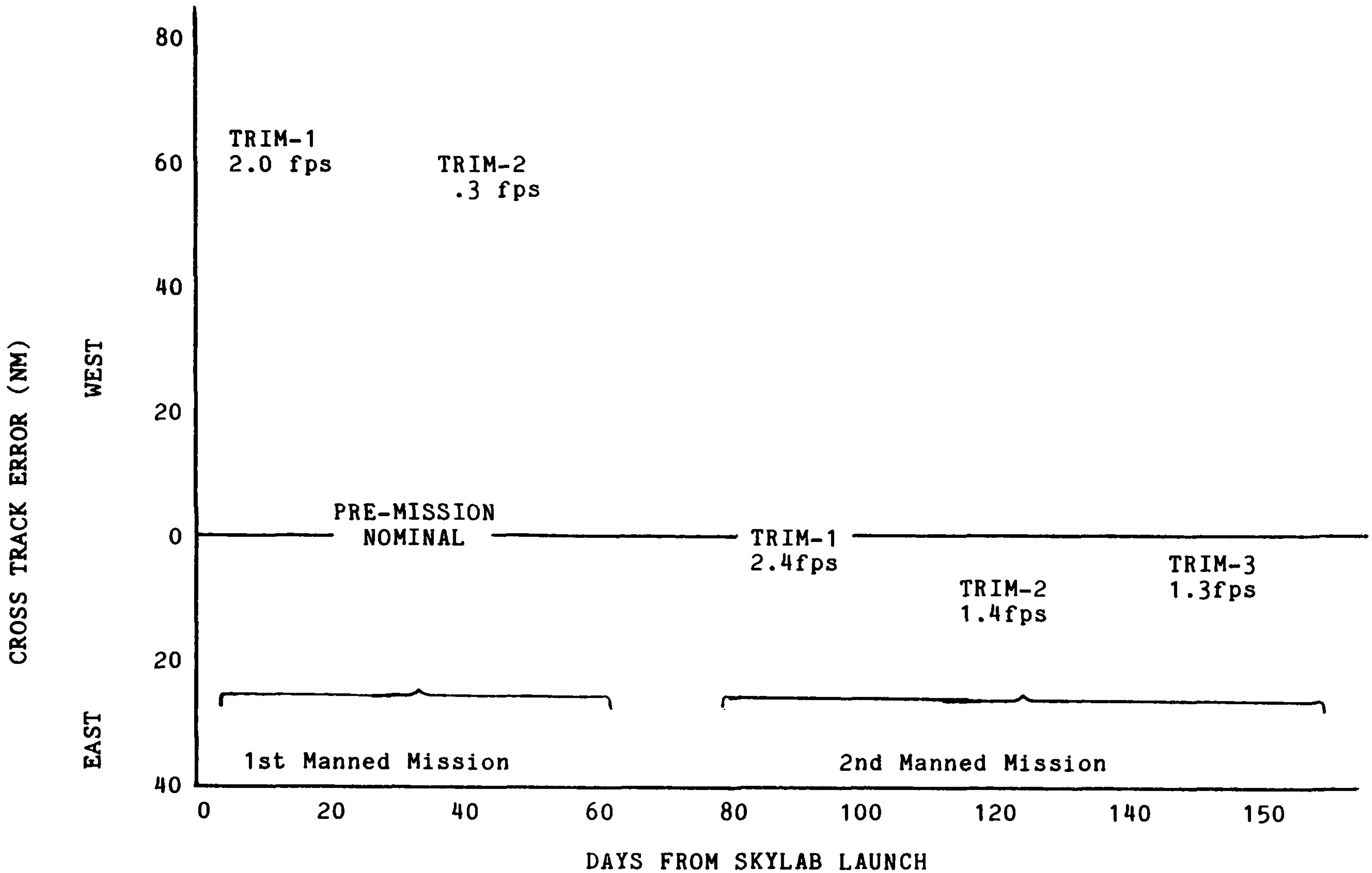

Fig. B-1 Skylab Orbit Trim Adjustment Maneuvers

APPENDIX C

Computer Programs

The computer models minimized by SUMT are contained in this appendix. Becuase of the similarity of the six models only the program listings for Models II and VI are included. For the sake of completeness Model II includes a listing of both the ETR and WTR problems. As with all the models the ETR and WTR problems are very similar. Wherever differences exist the margins are marked with a Δ or □ for ETR and WTR problems respectively.

For the sake of understandability the programs are internally documented and contain three different subroutines calculating OTV, Orbiter and SOC fuel consumption (subroutines STSOPT, ORBFUL and SOCFUL respectively). A fourth subrouting called RESTNT contains the problem objective function and constraints. The program readability is enhanced by consistent use of the same variable designations as contained within the text of the thesis. The SUMT library program is documented in Ref 9 and 10. The PROCES program uses SUMT as a nested optimization routine which is called sequentially and is documented in Ref 14,15,21 and 22. More detailed information on the programs can be obtained through the AFIT Department of Aeronautics and Astronautics, Capt. DeWispelare.

As with most Thesis efforts Murphy's law proved itself infallible once again. After completing more than one hundred computer runs on Models I through IV a sign error in the ETR MECO mass calculation was found (Marked in the margin of Computer Program C-1 with o). Fortunately, the impact was very minor and resulted only in a slightly conservative estimate of MECO mass and therefore payload mass for Models I through IV. The total error was only a couple of hundred kilograms or a fraction of a Shuttle launch, and it was corrected in Models V and VI. The errors are appropriately marked in the attached programs.

The vector optimization problem of Model VI would normally be accomplished by a program like PROCES. However, due to the simplicity of a dual objective problem the solution was implemented with a simple variation of Model V. A loop added to the program repeatedly used SUMT to minimize Shuttle launches subject to different average OTV mission durations. The latter were incorporated as equality constraints within the SUMT program. The resulting solutions were then manually checked to get the NDSS or efficient frontier.

Utilization of the SUMT program as a numerical minimization routine was particularly efficient in the single objective problems, models I through V. The total central processor time required to compile and execute the programs was around 0.5 seconds. The vector optimization problem with its multiple calls to SUMT was considerably less efficient.

Computer Program C-1 ETR Model II Launch Minimization Program

```
QTS,T35,I0100,CM100000.T820472,SP078
ATTACH,SUMT,SUMT,ID=AFIT.
LIBRARY,SUMT.
FTN(L=0).
LGO.
*EOR
      PROGRAM MAIN(INPUT,OUTPUT,SAVE,TAPE5=INPUT,TAPE6=OUTPUT,
     +    TAPE7=SAVE)
      REAL ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +     FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +     MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +     MPL,FORB,ISPOTV,ISPSOC,ISPORB
      INTEGER I,K
      COMMON/DEVC/NI,NO,NS
      COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +     PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +     MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
     +     ISPORB,H
      COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
      NI=5
      NO=6
      NS=7
C
C     ENTERS CONSTANT PROGRAM DATA
C
      DATA PI,U,W,PO,G,MET,MR/3.1415926535,398601.2,
     +     7.2922115856E-5,24.9,8.7,38399.0,88041.0/
C
C     ENTERS PROBLEM PARAMETER DATA
C
      DATA K,B,MOTV,MSOC,MCSOC/7,.02,2270.,100000.,20000./
      DATA H,ISPOTV,ISPSOC,ISPORB/30.0,455.0,455.0,313.0/
C
C     ENTERS SATELLITE TRAFFIC MODEL DATA
C
      DATA (ASAT(I),I=1,7)/41000.,20000.,6700.,65000.,
     +     25000.,12000.,6700./
      DATA (ESAT(I),I=1,7)/0.,0.,0.,0.,0.7,0.,0./
      DATA (ISAT(I),I=1,7)/0.,0.,28.5,55.,65.,90.,98./
      DATA (MSAT(I),I=1,7)/2000.,500.,25000.,1500.,
     +     1500.,4500.,8000./
      DATA (FSAT(I),I=1,7)/3.,.5,.5,4.,.5,3.,5./
      CALL SUMT
 10   FORMAT(//,4X,"ETR MODEL II LAUNCH ",
     +     "MINIMIZATION PROGRAM")
 15   FORMAT(4X,"=== ===== == ====== ",
     +     "============ =======")
      PRINT 10
      PRINT 15
 20   FORMAT(//," SATELLITE TRAFFIC MODEL")
```

```
           PRINT 20
      30   FORMAT(" --------- ------- -----",/)
           PRINT 30
      35   FORMAT(/,5X,"MISSION",3X,"ASAT",3X,"ESAT",3X,"ISAT",
     +          3X,"MSAT",4X,"FSAT",4X,"OTV FUEL")
      36    FORMAT(7X,"(#)",5X,"(KM)",10X,"(DEG)",2X,"(KG)",4X,
     +          "(LS/YR)",3X,"(KG)",/)
           PRINT 35
           PRINT 36
      40   FORMAT(6X,I3,5X,F6.0,2X,F4.2,3X,F5.1,1X,F7.0,2X,
     +          F5.2,2X,F8.0)
           DO 50 I=1,K
             PRINT 40,I,ASAT(I),ESAT(I),ISAT(I),
     +            MSAT(I),FSAT(I),MFMSN(I)
      50   CONTINUE
      60   FORMAT(/," VARIABLE PARAMETERS")
      70   FORMAT(" -------- ----------",/)
      80   FORMAT("      BALLISTIC COEFFICIENT (M**2/KG)=",F10.2)
      81   FORMAT("      SCALE HEIGHT (KM)              =",F10.2)
      82   FORMAT("      OTV MASS (KG)                  =",F10.2)
      83   FORMAT("      SOC MASS (KG)                  =",F10.2)
      84   FORMAT("      ANNUAL SOC CARGO MASS (KG/YR)  =",F10.2)
      85   FORMAT("      OTV SPECIFIC IMPULSE (SEC)     =",F10.2)
      86   FORMAT("      SOC SPECIFIC IMPULSE (SEC)     =",F10.2)
      87   FORMAT("      ORB SPECIFIC IMPULSE (SEC)     =",F10.2)
      90   FORMAT(/," FUEL CONSUMPTION")
      95   FORMAT(" ---- -----------",/)
      100  FORMAT("      ORBITER FUEL MASS (KG/MSN)     =",F10.2)
      101  FORMAT("      SOC FUEL MASS (KG/YR)          =",F10.2)
      102  FORMAT("      OTV FUEL MASS (KG/YR)          =",F10.2)
      103  FORMAT("      TOTAL STS FUEL MASS (KG/YR)    =",F10.2)
      110  FORMAT(/," SOC LOCATION AND RESUPPLY PARAMETERS")
      115  FORMAT(" --- -------- --- -------- ----------",/)
      120  FORMAT("      ORBIT INCLINATION (DEG)        =",F10.2)
      121  FORMAT("      ORBIT RADIUS (KM)              =",F10.2)
      122  FORMAT("      NO OF ORB LAUNCHES (LS/YR)     =",F10.2)
      123  FORMAT("      ORB PAYLOAD MASS (KG/MSN)      =",F10.2)
           DO 130 I=1,1
             PRINT 60
             PRINT 70
             PRINT 80,B
             PRINT 81,H
             PRINT 82,MOTV
             PRINT 83,MSOC
             PRINT 84,MCSOC
             PRINT 85,ISPOTV
             PRINT 86,ISPSOC
             PRINT 87,ISPORB
             PRINT 90
             PRINT 95
```

```
                PRINT 100,MFORB
                PRINT 101,MFSOC
                PRINT 102,MFOTV
                PRINT 103,FORB*MFORB+MFSOC+MFOTV
                PRINT 110
                PRINT 115
                PRINT 120,X(1)
                PRINT 121,X(2)
                PRINT 122,FORB
                PRINT 123,MPL
 130          CONTINUE
            END
            SUBROUTINE RESTNT(IN,VAL)
              REAL ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +             FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +             MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +             MPL,FORB,ISPOTV,ISPSOC,ISPORB
              COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +             PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +             MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
     +             ISPORB,H
              COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
C
C             X(1)=SOC INCLINATION : X(2)=SOC ALTITUDE
C
              IF(IN) 140,140,150
 140          CALL STSOPT(VAL)
              RETURN
C
C             INCLINATION, ALTITUDE AND FUEL CONSTRAINTS
C
 150          GOTO(151,152,153,154,155,156),IN
 151          VAL=X(1)-28.5
              RETURN
 152          VAL=57.0-X(1)
              RETURN
 153          VAL=X(2)-6500.0
              RETURN
 154          VAL=7200.0-X(2)
              RETURN
 155          CALL ORBFUL
              VAL=10830.0-MFORB
              RETURN
 156          CALL STSOPT(VAL)
              VAL=MPL-0.0
              RETURN
            END
            SUBROUTINE STSOPT(VAL)
C
C             CALCULATES OTV FUEL CONSUMPTION FOR K MISSIONS
```

```
C
          REAL ISOC,RSOC,MCSAT,VOTV,RASAT,M,P,R,S,T,
     +         ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +         FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +         MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +         MPL,FORB,ISPOTV,ISPSOC,ISPORB
          INTEGER I
          COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
          COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +         PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +         MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
     +         ISPORB,H
          MFOTV=0.0
          MCSAT=0.0
          ISOC=X(1)
          RSOC=X(2)
          DO 160 I=1,K
            RASAT=ASAT(I)*(1.0+ESAT(I))
            M=SQRT(ABS(2.0E6*U*(1.0/RSOC-1.0/(RASAT+RSOC))))
            P=SQRT(U*1.0E6/RSOC)
            R=1.0E6*U*(4.0/RASAT-1.0/ASAT(I)-2.0/(RASAT+RSOC))
            S=4.0E6*U*SQRT(ABS(((1.0/RASAT-0.5/ASAT(I))
     +           *(1.0/RASAT-1.0/(RASAT+RSOC)))))
            T=COS((ISOC-ISAT(I))*PI/180.0)
            VOTV=ABS(M-P)+SQRT(ABS(R-S*T))
            MFMSN(I)=(MSAT(I)+MOTV+MOTV*EXP(VOTV/(ISPOTV*G)))
     +           *(EXP(VOTV/(ISPOTV*G))-1.0)
            MFOTV=MFOTV+MFMSN(I)*FSAT(I)
            MCSAT=MCSAT+FSAT(I)*MSAT(I)
 160      CONTINUE
          CALL SOCFUL
          CALL ORBFUL
C
          CALCULATES TOTAL ANNUAL FUEL CONSUMPTION
C
          FORB=(MCSAT+MFOTV+MFSOC+MCSOC)/MPL
          VAL=FORB
        END
        SUBROUTINE ORBFUL
C
          CALCULATES ORBITER FUEL CONSUMPTION
C
        REAL ISOC,RSOC,MM,VORBA,VORBD,MFORBA,MFORBD,
     +       ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +       FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +       MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +       MPL,FORB,ISPOTV,ISPSOC,ISPORB
        COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +       PI,U.W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +       MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
```

```
     +      ISPORB,H
      COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
        ISOC=X(1)
        RSOC=X(2)
        MM=159275.829-3.3575*ISOC-3.70994*ISOC**2
     +       +0.01339*ISOC**3
        VORBA=-2.023703587E-5*RSOC**2+0.8474467398*RSOC
     +       -4623.658232
        VORBD=1.974610171E-4*RSOC**2-2.501373195*RSOC
     +       +7994.436774
        MPL=(MM-MET)*EXP(-VORBA/(ISPORB*G))
     +       -MR*EXP(VORBD/(ISPORB*G))
        MFORBA=(MM-MET)*(1.0-EXP(-VORBA/(ISPORB*G)))
        MFORBD=(MM-MET-MFORBA-MPL)
     +       *(1.0-EXP(-VORBD/(ISPORB*G)))
        MFORB=MFORBA+MFORBD
      END
      SUBROUTINE SOCFUL
C
C       CALCULATES SOC STATIONKEEPING FUEL CONSUMPTION
C
        REAL ISOC,RSOC,ASOC,F,
     +       ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +       FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +       MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +       MPL,FORB,ISPOTV,ISPSOC,ISPORB
        COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
        COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +       PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +       MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
     +       ISPORB,H
        ISOC=X(1)
        RSOC=X(2)
        F=0.00175*ISOC+0.84004
        ASOC=(U*B*PO*F
     +       *EXP((6498.0-RSOC)/H))/(2000*RSOC)
        MFSOC=(MSOC*ASOC*31557600)/(ISPSOC*G)
      END
*EOR
 $DATA N=2,M=6,X=28.,6500.,NT(5)=1,THETA0=1.E-12 $END
*EOR
```

Computer Program C-2 WTR Model II Launch Minimization Program

```
QTS,T35,IO100,CM100000.T820472,SP078
ATTACH,SUMT,SUMT,ID=AFIT.
LIBRARY,SUMT.
FTN(L=0).
LGO.
*EOR
              PROGRAM MAIN(INPUT,OUTPUT,SAVE,TAPE5=INPUT,TAPE6=OUTPUT,
     +          TAPE7=SAVE)
                REAL ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +               FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +               MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +               MPL,FORB,ISPOTV,ISPSOC,ISPORB
                INTEGER I,K
                COMMON/DEVC/NI,NO,NS
                COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +               PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +               MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
     +               ISPORB,H
                COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
                NI=5
                NO=6
                NS=7
C
C               ENTERS CONSTANT PROGRAM DATA
C
                DATA PI,U,W,PO,G,MET,MR/3.1415926535,398601.2,
     +               7.2922115856E-5,24.9,8.7,38399.0,88041.0/
C
C               ENTERS PROBLEM PARAMETER DATA
C
                DATA K,B,MOTV,MSOC,MCSOC/7,.02,2270.,100000.,20000./
                DATA H,ISPOTV,ISPSOC,ISPORB/30.0,455.0,455.0,313.0/
C
C               ENTERS SATELLITE TRAFFIC MODEL DATA
C
                DATA (ASAT(I),I=1,7)/41000.,20000.,6700.,65000.,
     +               25000.,12000.,6700./
                DATA (ESAT(I),I=1,7)/0.,0.,0.,0.,0.7,0.,0./
                DATA (ISAT(I),I=1,7)/0.,0.,28.5,55.,65.,90.,98./
                DATA (MSAT(I),I=1,7)/2000.,500.,25000.,1500.,
     +               1500.,4500.,8000./
                DATA (FSAT(I),I=1,7)/3.,.5,.5,4.,.5,3.,5./
                CALL SUMT
 10             FORMAT(//,4X,"WTR MODEL II LAUNCH ",
     +               "MINIMIZATION PROGRAM")
 15             FORMAT(4X,"=== ===== == ====== ",
     +               "============ =======")
                PRINT 10
                PRINT 15
 20             FORMAT(//," SATELLITE TRAFFIC MODEL")
```

```
            PRINT 20
 30         FORMAT(" --------- ------- -----",/)
            PRINT 30
 35         FORMAT(/,5X,"MISSION",3X,"ASAT",3X,"ESAT",3X,"ISAT",
     +          3X,"MSAT",4X,"FSAT",4X,"OTV FUEL")
 36          FORMAT(7X,"(#)",5X,"(KM)",10X,"(DEG)",2X,"(KG)",4X,
     +          "(LS/YR)",3X,"(KG)",/)
            PRINT 35
            PRINT 36
 40         FORMAT(6X,I3,5X,F6.0,2X,F4.2,3X,F5.1,1X,F7.0,2X,
     +          F5.2,2X,F8.0)
            DO 50 I=1,K
              PRINT 40,I,ASAT(I),ESAT(I),ISAT(I),
     +            MSAT(I),FSAT(I),MFMSN(I)
 50         CONTINUE
 60         FORMAT(/," VARIABLE PARAMETERS")
 70         FORMAT(" -------- ----------",/)
 80         FORMAT("     BALLISTIC COEFFICIENT (M**2/KG)=",F10.2)
 81         FORMAT("     SCALE HEIGHT (KM)              =",F10.2)
 82         FORMAT("     OTV MASS (KG)                  =",F10.2)
 83         FORMAT("     SOC MASS (KG)                  =",F10.2)
 84         FORMAT("     ANNUAL SOC CARGO MASS (KG/YR)  =",F10.2)
 85         FORMAT("     OTV SPECIFIC IMPULSE (SEC)     =",F10.2)
 86         FORMAT("     SOC SPECIFIC IMPULSE (SEC)     =",F10.2)
 87         FORMAT("     ORB SPECIFIC IMPULSE (SEC)     =",F10.2)
 90         FORMAT(/," FUEL CONSUMPTION")
 95         FORMAT(" ---- -----------",/)
 100        FORMAT("     ORBITER FUEL MASS (KG/MSN)     =",F10.2)
 101        FORMAT("     SOC FUEL MASS (KG/YR)          =",F10.2)
 102        FORMAT("     OTV FUEL MASS (KG/YR)          =",F10.2)
 103        FORMAT("     TOTAL STS FUEL MASS (KG/YR)    =",F10.2)
 110        FORMAT(/," SOC LOCATION AND RESUPPLY PARAMETERS")
 115        FORMAT(" --- -------- --- -------- ----------",/)
 120        FORMAT("     ORBIT INCLINATION (DEG)        =",F10.2)
 121        FORMAT("     ORBIT RADIUS (KM)              =",F10.2)
 122        FORMAT("     NO OF ORB LAUNCHES (LS/YR)     =",F10.2)
 123        FORMAT("     ORB PAYLOAD MASS (KG/MSN)      =",F10.2)
            DO 130 I=1,1
              PRINT 60
              PRINT 70
              PRINT 80,B
              PRINT 81,H
              PRINT 82,MOTV
              PRINT 83,MSOC
              PRINT 84,MCSOC
              PRINT 85,ISPOTV
              PRINT 86,ISPSOC
              PRINT 87,ISPORB
              PRINT 90
              PRINT 95
```

```
              PRINT 100,MFORB
              PRINT 101,MFSOC
              PRINT 102,MFOTV
              PRINT 103,FORB*MFORB+MFSOC+MFOTV
              PRINT 110
              PRINT 115
              PRINT 120,X(1)
              PRINT 121,X(2)
              PRINT 122,FORB
              PRINT 123,MPL
130         CONTINUE
          END
          SUBROUTINE RESTNT(IN,VAL)
            REAL ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +           FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +           MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +           MPL,FORB,ISPOTV,ISPSOC,ISPORB
            COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +           PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +           MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
     +           ISPORB,H
            COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
C
C           X(1)=SOC INCLINATION : X(2)=SOC ALTITUDE
C
            IF(IN) 140,140,150
140         CALL STSOPT(VAL)
            RETURN
C
C           INCLINATION, ALTITUDE AND FUEL CONSTRAINTS
C
150         GOTO(151,152,153,154,155,156),IN
151         VAL=X(1)-56.0
            RETURN
152         VAL=104.0-X(1)
            RETURN
153         VAL=X(2)-6500.0
            RETURN
154         VAL=7200.0-X(2)
            RETURN
155         CALL ORBFUL
            VAL=10830.0-MFORB
            RETURN
156         CALL STSOPT(VAL)
            VAL=MPL-0.0
            RETURN
          END
          SUBROUTINE STSOPT(VAL)
C
C           CALCULATES OTV FUEL CONSUMPTION FOR K MISSIONS
```

```
C
      REAL ISOC,RSOC,MCSAT,VOTV,RASAT,M,P,R,S,T,
     +     ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +     FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +     MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +     MPL,FORB,ISPOTV,ISPSOC,ISPORB
      INTEGER I
      COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
      COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +     PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +     MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
     +     ISPORB,H
      MFOTV=0.0
      MCSAT=0.0
      ISOC=X(1)
      RSOC=X(2)
      DO 160 I=1,K
        RASAT=ASAT(I)*(1.0+ESAT(I))
        M=SQRT(ABS(2.0E6*U*(1.0/RSOC-1.0/(RASAT+RSOC))))
        P=SQRT(U*1.0E6/RSOC)
        R=1.0E6*U*(4.0/RASAT-1.0/ASAT(I)-2.0/(RASAT+RSOC))
        S=4.0E6*U*SQRT(ABS(((1.0/RASAT-0.5/ASAT(I))
     +       *(1.0/RASAT-1.0/(RASAT+RSOC)))))
        T=COS((ISOC-ISAT(I))*PI/180.0)
        VOTV=ABS(M-P)+SQRT(ABS(R-S*T))
        MFMSN(I)=(MSAT(I)+MOTV+MOTV*EXP(VOTV/(ISPOTV*G)))
     +       *(EXP(VOTV/(ISPOTV*G))-1.0)
        MFOTV=MFOTV+MFMSN(I)*FSAT(I)
        MCSAT=MCSAT+FSAT(I)*MSAT(I)
  160 CONTINUE
      CALL SOCFUL
      CALL ORBFUL
C
C     CALCULATES TOTAL ANNUAL FUEL CONSUMPTION
C
      FORB=(MCSAT+MFOTV+MFSOC+MCSOC)/MPL
      VAL=FORB
    END
    SUBROUTINE ORBFUL
C
C     CALCULATES ORBITER FUEL CONSUMPTION
C
    REAL ISOC,RSOC,MM,VORBA,VORBD,MFORBA,MFORBD,
     +   ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +   FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +   MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +   MPL,FORB,ISPOTV,ISPSOC,ISPORB
    COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +   PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +   MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
```

```
     +      ISPORB,H
      COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
        ISOC=X(1)
        RSOC=X(2)
        MM=164628.209-79.17494*ISOC-3.01734*ISOC**2
     +       +0.01256*ISOC**3
        VORBA=-2.023703587E-5*RSOC**2+0.8474467398*RSOC
     +       -4623.658232+85.65
        VORBD=1.974610171E-4*RSOC**2-2.501373195*RSOC
     +       +7994.436774
        MPL=(MM-MET)*EXP(-VORBA/(ISPORB*G))
     +       -MR*EXP(VORBD/(ISPORB*G))
        MFORBA=(MM-MET)*(1.0-EXP(-VORBA/(ISPORB*G)))
        MFORBD=(MM-MET-MFORBA-MPL)
     +       *(1.0-EXP(-VORBD/(ISPORB*G)))
        MFORB=MFORBA+MFORBD
      END
      SUBROUTINE SOCFUL
C
C       CALCULATES SOC STATIONKEEPING FUEL CONSUMPTION
C
        REAL ISOC,RSOC,ASOC,F,
     +       ASAT(35),ESAT(35),ISAT(35),MSAT(35),
     +       FSAT(35),MFMSN(35),PI,U,W,PO,G,MET,
     +       MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +       MPL,FORB,ISPOTV,ISPSOC,ISPORB
        COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
        COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +       PI,U,W,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,
     +       MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,
     +       ISPORB,H
        ISOC=X(1)
        RSOC=X(2)
        F=0.00175*ISOC+0.84004
        ASOC=(U*B*PO*F
     +       *EXP((6498.0-RSOC)/H))/(2000*RSOC)
        MFSOC=(MSOC*ASOC*31557600)/(ISPSOC*G)
      END
*EOR
 $DATA N=2,M=6,X=56.,6500.,NT(5)=1,THETA0=1.E-12 $END
*EOR
```

Computer Program C-3   ETR Model VI Dual Objective Minimization Program

```
QTS,T300,IO100,CM100000.T820472,SP078
ATTACH,SUMT,SUMT,ID=AFIT.
LIBRARY,SUMT.
FTN(L=0,PL=10000).
LGO.
*EOR
          PROGRAM MAIN(INPUT,OUTPUT,SAVE,TAPE5=INPUT,
     +       TAPE6=OUTPUT,TAPE7=SAVE)
          REAL ASAT(35),ESAT(35),ISAT(35),MSAT(35),ISPCHM,LOWTOF,
     +       FSAT(35),MFMSN(35),PI,U,PO,G,MET,
     +       MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +       MPL,FORB,ISPOTV,ISPSOC,ISPORB,MSP,STEP,
     +       MTHR,PWR,MFT,THRUST,TIMRTN(35),TIMDPL(35),
     +       TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
          INTEGER I,K,POINT,TOTPTS
          COMMON/DEVC/NI,NO,NS
          COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +       PI,U,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,ISPCHM,
     +       MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,MSP,
     +       ISPORB,H,MTHR,PWR,MFT,THRUST,TIMRTN,TIMDPL,
     +       TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
          COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
          NI=5
          NO=6
          NS=7
C
C         ENTERS LOW VALUE OF SECOND OBJECTIVE FUNCTION
C           (LOWTOF), STEP INTERVAL BY WHICH IT IS
C           INCREMENTED AND THE TOTAL NUMBER OF POINTS
C           EVALUATED.
C
          DATA LOWTOF,STEP,TOTPTS/400.,-20.,20/
C
C         ENTERS CONSTANT PROGRAM DATA
C
          DATA PI,U,PO,G,MET,MR/3.1415926535,398601.2,
     +       24.9,8.7,38399.0,85000.0/
C
C         ENTERS PROBLEM PARAMETER DATA
C
          DATA K,B,MSOC,MCSOC,MSP/7,.02,100000.,20000.,10./
          DATA H.ISPOTV,ISPSOC,ISPORB/30.0,2900.0,2900.0,313.0/
          DATA MTHR,PWR,MFT,THRUST/51.36,3.06,12.0,.129/
          DATA MCMOTV,ISPCHM/2270.0,455.0/
C
C         ENTERS SATELLITE TRAFFIC MODEL DATA
C
          DATA (ASAT(I),I=1,7)/41000.,20000.,6700.,65000.,
     +       25000.,12000.,6700./
          DATA (ESAT(I),I=1,7)/0.,0.,0.,0.,0.7,0.,0./
```

```
      DATA (ISAT(I),I=1,7)/0.,0.,28.5,55.,65.,90.,98./
      DATA (MSAT(I),I=1,7)/2000.,500.,25000.,1500.,
     +    1500.,4500.,8000./
      DATA (FSAT(I),I=1,7)/2.25,.375,.375,3.0,.375,2.25,3.75/
C
C     LOOP TO INCREMENT 2ND OBJ. FUNCTION, THE ION OTV
C       AVERAGE TIME OF FLIGHT (AVGTOF)
C
      AVGTOF=LOWTOF
      DO 130 POINT=1,TOTPTS
 2      FORMAT(//,10X,"ION OTV TIME OF FLIGHT IS ",F10.2)
        PRINT 2,AVGTOF
        CALL SUMT
 10     FORMAT(//,4X,"ETR MODEL VI DUAL OBJECTIVE ",
     +     "MINIMIZATION PROGRAM")
 15     FORMAT(4X,"=== ===== == ==== ========= ",
     +     "============ =======")
        PRINT 10
        PRINT 15
 20     FORMAT(/," SATELLITE TRAFFIC MODEL")
        PRINT 20
 30     FORMAT(" --------- ------- -----")
        PRINT 30
 35     FORMAT("MSN",3X,"ASAT",2X,"ESAT",2X,"ISAT",2X,
     +    "MSAT",2X,"FSAT",3X,"OTV",3X,"DEPLOY",2X,"RETURN")
 36     FORMAT(37X,"FUEL",3X,"TIME",4X,"TIME")
 37     FORMAT(1X,"#",5X,"KM",9X,"DEG",4X,"KG",3X,"#/YR",
     +     4X,"KG",4X,"DAYS",4X,"DAYS",/)
        PRINT 35
        PRINT 36
        PRINT 37
 40     FORMAT(I2,2X,F7.0,1X,F4.3,1X,F5.1,1X,F6.0,
     +     1X,F4.2,1X,F7.0,1X,F6.1,2X,F6.1)
        DO 50 I=1,K
          PRINT 40,I,ASAT(I),ESAT(I),ISAT(I),
     +       MSAT(I),FSAT(I),MFMSN(I),
     +       TIMDPL(I)/86400.,TIMRTN(I)/86400.
 50     CONTINUE
 60     FORMAT(/," CONSTANT PARAMETERS")
 70     FORMAT(" -------- ----------")
 72     FORMAT("      ION THRUSTER MASS (KG)              =",F10.2)
 73     FORMAT("      THRUSTER FUEL TANK MASS (KG)        =",F10.2)
 74     FORMAT("      SPECIFIC MASS (KG/KW)               =",F10.2)
 75     FORMAT("      THRUSTER POWER (KW/THRUSTER)        =",F10.2)
 76     FORMAT("      ION THRUSTER THRUST (MN)            =",F10.2)
 77     FORMAT("      NUMBER OF OTV ION THRUSTERS (#)=",F10.2)
 78     FORMAT("      EXPENDED MASS AT ETS (KG)           =",F10.2)
 79     FORMAT("      SHUTTLE REFERENCE MASS (KG)         =",F10.2)
 80     FORMAT("      BALLISTIC COEFFICIENT (M**2/KG)=",F10.2)
 81     FORMAT("      SCALE HEIGHT (KM)                   =",F10.2)
```

```
82      FORMAT("      ION OTV MASS (KG)                 =",F10.2)
89      FORMAT("      CHEMICAL OTV MASS (KG)            =",F10.2)
83      FORMAT("      SOC MASS (KG)                     =",F10.2)
84      FORMAT("      ANNUAL SOC CARGO MASS (KG/YR)     =",F10.2)
88      FORMAT("      CHEMICAL OTV SPECIFIC IMPULSE     =",F10.2)
85      FORMAT("      ION OTV SPECIFIC IMPULSE (SEC)    =",F10.2)
86      FORMAT("      SOC SPECIFIC IMPULSE (SEC)        =",F10.2)
87      FORMAT("      ORB SPECIFIC IMPULSE (SEC)        =",F10.2)
90      FORMAT(" FUEL CONSUMPTION")
95      FORMAT(" ---- -----------")
100     FORMAT("      ORBITER FUEL MASS (KG/MSN)        =",F10.2)
101     FORMAT("      SOC FUEL MASS (KG/YR)             =",F10.2)
102     FORMAT("      OTV FUEL MASS (KG/YR)             =",F10.2)
103     FORMAT("      TOTAL STS FUEL MASS (KG/YR)       =",F10.2)
110     FORMAT(" SOC LOCATION AND RESUPPLY PARAMETERS")
115     FORMAT(" --- -------- --- -------- ----------")
120     FORMAT("      ORBIT INCLINATION (DEG)           =",F10.2)
121     FORMAT("      ORBIT RADIUS (KM)                 =",F10.2)
122     FORMAT("      NO OF ORB LAUNCHES (LS/YR)        =",F10.2)
123     FORMAT("      ORB PAYLOAD MASS (KG/MSN)         =",F10.2)
124     FORMAT("      NO OF ION PROPELLED OTV'S (#)     =",F10.2)
125     FORMAT("      AVG OTV TIME OF FLIGHT (DAYS)     =",F10.2)
126     FORMAT("      PAYLOAD MASS TO SOC (KG)          =",F10.2)
        PRINT 60
        PRINT 70
        PRINT 72,MTHR
        PRINT 73,MFT
        PRINT 74,MSP
        PRINT 75,PWR
        PRINT 76,THRUST*1000.0
        PRINT 78,MET
        PRINT 79,MR
        PRINT 80,B
        PRINT 81,H
        PRINT 89,MCMOTV
        PRINT 83,MSOC
        PRINT 84,MCSOC
        PRINT 88,ISPCHM
        PRINT 85,ISPOTV
        PRINT 86,ISPSOC
        PRINT 87,ISPORB
        PRINT 90
        PRINT 95
        PRINT 100,MFORB
        PRINT 101,MFSOC
        PRINT 102,MFOTV+FORB*(MFOTVA+MFOTVD)
        PRINT 103,FORB*(MFORB+MFOTVA+MFOTVD)+MFSOC+MFOTV
        PRINT 110
        PRINT 115
        PRINT 120,X(1)
```

```
                PRINT 121,X(2)
                PRINT 77,X(3)
                PRINT 122,FORB
                PRINT 125,TIMTOT/K
                PRINT 82,MOTV
                PRINT 124,NOOTV
                PRINT 123,MPL
                PRINT 126,MPL-MFOTVA
                AVGTOF=AVGTOF+STEP
 130      CONTINUE
        END
        SUBROUTINE RESTNT(IN,VAL)
          REAL ASAT(35),ESAT(35),ISAT(35),MSAT(35),ISPCHM,
     +         FSAT(35),MFMSN(35),PI,U,PO,G,MET,
     +         MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +         MPL,FORB,ISPOTV,ISPSOC,ISPORB,MSP,
     +         MTHR,PWR,MFT,THRUST,TIMRTN(35),TIMDPL(35),
     +         TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
          COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +         PI,U,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,ISPCHM,
     +         MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,MSP,
     +         ISPORB,H,MTHR,PWR,MFT,THRUST,TIMRTN,TIMDPL,
     +         TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
          COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
C
C         X(1)=SOC INCLINATION : X(2)=SOC RADIUS
C         X(3)=NUMBER OF OTV ION THRUSTERS
C
          IF(IN) 140,140,150
 140      CALL STSOPT(VAL)
          RETURN
C
C         INCLINATION, ALTITUDE AND FUEL CONSTRAINTS
C
 150      GOTO(151,152,153,154,155,156,157,158),IN
 151      VAL=X(1)-28.5
          RETURN
 152      VAL=57.0-X(1)
          RETURN
 153      VAL=X(2)-6500.0
          RETURN
 154      VAL=X(3)-0.0
          RETURN
 155      CALL ORBFUL
          VAL=10830.0-MFORB
          RETURN
 156      CALL STSOPT(VAL)
          VAL=MPL-MFOTVA-0.0
          RETURN
 157      CALL STSOPT(VAL)
```

```
            VAL=NOOTV-0.0
            RETURN
  158       CALL STSOPT(VAL)
            VAL=TIMTOT/K-AVGTOF
            RETURN
          END
          SUBROUTINE STSOPT(VAL)
C
C           CALCULATES OTV FUEL CONSUMPTION FOR K MISSIONS
C
            REAL ISOC,RSOC,MCSAT,VOTV,RASAT,TEMP,
     +           ASAT(35),ESAT(35),ISAT(35),MSAT(35),ISPCHM,
     +           FSAT(35),MFMSN(35),PI,U,PO,G,MET,
     +           MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +           MPL,FORB,ISPOTV,ISPSOC,ISPORB,MSP,
     +           MTHR,PWR,MFT,THRUST,MFRTN,MFDPL,
     +           TIMRTN(35),TIMDPL(35),
     +           TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
            INTEGER I
            COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
            COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +           PI,U,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,ISPCHM,
     +           MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,MSP,
     +           ISPORB,H,MTHR,PWR,MFT,THRUST,TIMRTN,TIMDPL,
     +           TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
            TIMTOT=0.0
            MFOTV=0.0
            MCSAT=0.0
            ISOC=X(1)
            RSOC=X(2)
            MOTV=X(3)*(MTHR+MSP*PWR+MFT)+300.
            DO 160 I=1,K
              VOTV=(ABS((ASAT(I)/6378.145)**(-.5)
     +             -(RSOC/6378.145)**(-.5))
     +             +PI*ABS((ISAT(I)-ISOC)*PI/180.0)
     +             /(2.0*SQRT(ASAT(I)/6378.145)))*7905.36828
              TEMP=EXP(VOTV/(ISPOTV*G))-1.0
              MFRTN=MOTV*TEMP
              TIMRTN(I)=(MFRTN*ISPOTV*G)/(X(3)*THRUST)
              MFDPL=(MSAT(I)+MOTV+MFRTN)*TEMP
              TIMDPL(I)=(MFDPL*ISPOTV*G)/(X(3)*THRUST)
              MFMSN(I)=MFRTN+MFDPL
              TIMTOT=TIMTOT+(TIMDPL(I)+TIMRTN(I))/86400.
              MFOTV=MFOTV+MFMSN(I)*FSAT(I)
              MCSAT=MCSAT+FSAT(I)*MSAT(I)
  160       CONTINUE
            NOOTV=TIMTOT/365.25
            CALL SOCFUL
            CALL ORBFUL
C
C           CALCULATES OTV FUEL NEEDED TO RENDEZVOUS WITH ORBITER
C
```

```
      IINT=X(1)
      RINT=6538.1
      M=SQRT(ABS(2.0E6*U*(1.0/RINT-1.0/(RINT+RSOC))))
      P=SQRT(U*1.0E6/RINT)
      R=1.0E6*U*(3.0/RSOC-2.0/(RSOC+RINT))
      S=4.0E6*U*SQRT(ABS((1.0/(2.0*RSOC))
     +     *(1.0/RSOC-1.0/(RSOC+RINT))))
      T=COS((IINT-ISOC)*PI/180.0)
      VOTV=ABS(M-P)+SQRT(ABS(R-S*T))
      MFOTVD=MCMOTV*(EXP(VOTV/(ISPCHM*G))-1.0)
      MFOTVA=(MCMOTV+MPL)*(1.0-EXP(-VOTV/(ISPCHM*G)))
C
C     CALCULATES TOTAL ANNUAL FUEL CONSUMPTION
C
      FORB=(MCSAT+MFOTV+MFSOC+MCSOC+(MOTV*NOOTV)/16.0)/
     +     (MPL-MFOTVA-MFOTVD)
      VAL=FORB
    END
    SUBROUTINE ORBFUL
C
C     CALCULATES ORBITER FUEL CONSUMPTION
C
    REAL IINT,RINT,MM,VORBA,VORBD,MFORBA,MFORBD,
   +     ASAT(35),ESAT(35),ISAT(35),MSAT(35),ISPCHM,
   +     FSAT(35),MFMSN(35),PI,U,PO,G,MET,
   +     MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
   +     MPL,FORB,ISPOTV,ISPSOC,ISPORB,MSP,
   +     MTHR,PWR,MFT,THRUST,TIMRTN(35),TIMDPL(35),
   +     TIMTOT,NOOTV,AVGTOF,MFOTVA,MFOTVD,MCMOTV
    COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
   +     PI,U,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,ISPCHM,
   +     MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,MSP,
   +     ISPORB,H,MTHR,PWR,MFT,THRUST,TIMRTN,TIMDPL,
   +     TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
    COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
      IINT=X(1)
      RINT=6538.1
      MM=159275.829+3.3575*IINT-3.70994*IINT**2
     +     +0.01339*IINT**3
      VORBA=51.7
      VORBD=84.1
      MPL=(MM-MET)*EXP(-VORBA/(ISPORB*G))
     +     -MR*EXP(VORBD/(ISPORB*G))
      MFORBA=(MM-MET)*(1.0-EXP(-VORBA/(ISPORB*G)))
      MFORBD=(MM-MET-MFORBA-MPL)
     +     *(1.0-EXP(-VORBD/(ISPORB*G)))
      MFORB=MFORBA+MFORBD
    END
```

```
      SUBROUTINE SOCFUL
C
C       CALCULATES SOC STATIONKEEPING FUEL CONSUMPTION
C
        REAL ISOC,RSOC,ASOC,F,
     +       ASAT(35),ESAT(35),ISAT(35),MSAT(35),ISPCHM,
     +       FSAT(35),MFMSN(35),PI,U,PO,G,MET,
     +       MR,B,MOTV,MSOC,MCSOC,MFOTV,MFSOC,MFORB,
     +       MPL,FORB,ISPOTV,ISPSOC,ISPORB,MSP,
     +       MTHR,PWR,MFT,THRUST,TIMRTN(35),TIMDPL(35),
     +       TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
        COMMON/SHARE/X(100),DEL(100),A(100,100),N(5)
        COMMON/VALUES/ASAT,ESAT,ISAT,MSAT,FSAT,MFMSN,
     +       PI,U,PO,G,MET,MR,K,B,MOTV,MSOC,MCSOC,ISPCHM,
     +       MFOTV,MFSOC,MFORB,MPL,FORB,ISPOTV,ISPSOC,MSP,
     +       ISPORB,H,MTHR,PWR,MFT,THRUST,TIMRTN,TIMDPL,
     +       TIMTOT,NOOTV,AVGTOF,RINT,MFOTVA,MFOTVD,MCMOTV
        ISOC=X(1)
        RSOC=X(2)
        F=0.00175*ISOC+0.84004
        ASOC=(U*B*PO*F
     +       *EXP((6498.0-RSOC)/H))/(2000*RSOC)
        MFSOC=(MSOC*ASOC*31557600)/(ISPSOC*G)
      END
*EOR
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
 $DATA N=3,M=7,MZ=1,X=28.,6500.,1.,NT(5)=1,THETAO=1.E-3 $END
```

APPENDIX D

Operational Computer Runs

Over a hundred computer runs were accomplished for this thesis effort. Table D-1 lists all of the runs and the configuration of the Model during the run. The configuration includes the particular scenario considered, the number of satellite missions serviced and any parameters that are varied. In addition, the output of selected computer runs are included for those requiring a more detailed understanding of the different models and scenarios. The minor MECO mass sign error discussed in Appendix C was corrected in all of the attached computer runs. Thus, the attached Model II and III results are more accurate than the results of Section 4.0 although the differences are very small.

Table D-1 Computer Runs Accomplished

Run #	Model #	Launch Range	SOC Scen-ario	Satellite Traffic Model	Varied Para-meters	
1	I	ETR	C	1-5	None	
2	"	"	A	1-7	"	
3	"	"	D	4-5	"	
4	"	ETR	B,D	1-3	"	
5	I	WTR	C,D	6-7	"	
6	"	"	B	4-7	"	
7	"	"	A	1-7	"	
8	"	"	D	4-5	"	
9	II	ETR	A	1-7	"	
10	"	"	B,D	1-3	"	
11	II	"	D	4-5	"	
12	"	"	C	1-5	"	
13	II	WTR	B	4-7	"	
14	"	"	D	4-5	"	
15	"	"	C,D	6-7	"	
16	"	"	A	1-7	"	
17	II	ETR	A	1-7	B	= .01
18	"	"	"	"	"	= .03
19	"	"	"	"	H	= 15
20	"	"	"	"	"	= 45
21	II	ETR	A	1-7	M_{otv}	= 1135
22	"	"	"	"	"	= 3405
23	"	"	"	"	M_{soc}	= 50000
24	"	"	"	"	"	= 100000
25	II	ETR	A	1-7	MC_{soc}	= 10000
26	"	"	"	"	"	= 30000

Table D-1 Computer Runs Accomplished (Cont.)

Run #	Model #	Launch Range	SOC Scenario	Satellite Traffic Model	Varied Parameters
27	II	ETR	A	1-7	ISP_{otv} = 9000
28	"	"	"	"	ISP_{otv} = ISP_{soc} = 5000
29	"	"	"	"	ISP_{otv} = 2900
30	"	"	"	"	ISP_{otv} = ISP_{soc} = 9000
31	II	ETR	A	1-7	ISP_{otv} = ISP_{soc} = 2900
32	"	"	"	"	" " = 10000
33	"	"	"	"	" " = 30000
34	"	"	"	"	" " = 20000
35	II	ETR	A	1-7	ISP_{otv} = 227.5
36	"	"	"	"	" = 682.5
37	"	"	"	"	ISP_{soc} = 227.5
38	"	"	"	"	ISP_{soc} = 682.5
39	II	ETR	A	1-7	ISP_{orb} = 156.5
40	"	"	"	"	" = 469.5
41	"	"	"	"	F_{sat} - Very Low
42	"	"	"	"	" - Low
43	"	"	"	"	" - High
44	"	"	"	"	" - Very High
45	II	ETR	A	1-7	I_{soc} 30° - 100°
46	"	"	"	"	R_{soc} 6500 - 7200
47	II	ETR	A	1-7	Years, 1-4
48	"	"	"	"	" 5-8
49	"	"	"	"	" 9-12
50	"	"	"	"	" 13-16
51	II	ETR	A	1-7	M_{et} = 34559.1
52	"	"	"	"	" = 42238.9

Table D-1 Computer Runs Accomplished (Cont.)

Run #	Model #	Launch Range	SOC Scen-ario	Satellite Traffic Model	Varied Para-meters	
53	II	ETR	A	1-7	M_r	= 79236.9
54	"	"	"	"	"	= 96845.1
55	III	ETR	A	1-7	None	
56	"	"	C	1-5	"	
57	"	WTR	A	1-7	"	
58	"	"	C	6-7	"	
59	III	ETR	A	1-7	M_{otv}	= 1135
60	"	"	"	"	"	= 3405
61	"	"	"	"	ISP_{otv}	= 227.5
62	"	"	"	"	"	= 682.5
63	III	ETR	A	1-7	ISP_{otv}	= 2900
64	"	"	"	"	"	= 9000
65	"	"	"	"	ISP_{orb}	= 156.5
66	"	"	"	"	"	= 469.5
67	III	ETR	A	1-7	M_r	= 79236.9
68	"	"	"	"	"	= 96845.1
69	IV	ETR	A	1-7	ISP_{otv}	= 9000
70	"	"	"	"	"	= ISP_{soc} = 5000
71	"	"	"	"	"	= 2900
72	"	"	"	"	"	= ISP_{soc} = 9000
73	IV	ETR	A	1-7	ISP_{otv}	= ISP_{soc} = 2900
74	"	"	"	"	"	= " = 10000
75	"	"	"	"	"	= " = 30000
76	"	"	"	"	"	= " = 20000
77	IV	ETR	A	1-7	None	
78	"	"	B	1-3	"	

Table D-1 Computer Runs Accomplished (Cont.)

Run #	Model #	Launch Range	SOC Scenario	Satellite Traffic Model	Varied Parameters
79	IV	ETR	C	1-5	None
80	"	WTR	A	1-7	"
81	"	"	B	4-7	"
82	"	"	C	6-7	"
83	III	ETR	B	1-3	"
84	"	WTR	B	4-7	"
85	III	ETR	A	1-7	M_r = 79236.9
86	"	"	"	"	" = 96845.1
87	"	"	"	"	ISP_{orb} = 156.5
88	"	"	"	"	" = 469.5
89	III	ETR	A	1-7	Thrust = .1935
90	"	"	"	"	" = .0645
91	"	"	"	"	N = 10
92	"	"	"	"	" = 30
93	III	ETR	A	1-7	M_{thr} = 25.68
94	"	"	"	"	" = 77.04
95	"	"	"	"	P_{wr} = 1.53
96	"	"	"	"	P_{wr} = 4.59
97	III	ETR	A	1-7	M_{sp} = 5
98	"	"	"	"	" = 15
99	V	ETR	A	1-7	None
100	"	"	B	1-3	"
101	"	"	C	1-5	"
102	"	WTR	A	1-7	"
103	"	"	B	4-7	"
104	"	"	C	6-7	"

Table D-1 Computer Runs Accomplished (Cont.)

Run #	Model #	Launch Range	SOC Scen-ario	Satellite Traffic Model	Varied Para-meters
105	VI	ETR	A	1-7	Standard Parameters TOF=300,280,...
106	"	"	"	"	Standard Parameters TOF=300,320,...
107	"	WTR	"	"	Level I Technology TOF=400,380,...
108	"	ETR	"	"	Level I Technology TOF=400,380,...
109	"	"	B	1-3	Level I Technology $I_{soc}=28.5^{o}$ TOF=400,380,...
110	"	"	A	1-7	Level II Technology TOF=400,380,...
111	"	"	A	"	Level III Technology TOF=400,380,...
112	"	"	B	4-7	Level I Technology $I_{soc}=57.0^{o}$ TOF=400,380,...
113	"	WTR	B	4-7	Level I Technology TOF=400,380,...

Computer Run D-1 Run Number 9

```
    ETR MODEL II LAUNCH MINIMIZATION PROGRAM
    === ===== == ====== ============ =======


SATELLITE TRAFFIC MODEL
--------- ------- -----


    MISSION     ASAT    ESAT     ISAT    MSAT     FSAT     OTV FUEL
      (#)       (KM)            (DEG)    (KG)    (LS/YR)     (KG)

       1      41000.    0.00      0.0    2000.    3.00      31577.
       2      20000.    0.00      0.0     500.     .50      36754.
       3       6700.    0.00     28.5   25000.     .50      53592.
       4      65000.    0.00     55.0    1500.    4.00      18370.
       5      25000.     .70     65.0    1500.     .50       7953.
       6      12000.    0.00     90.0    4500.    3.00      24841.
       7       6700.    0.00     98.0    8000.    5.00      55980.

VARIABLE PARAMETERS
-------- ----------

    BALLISTIC COEFFICIENT (M**2/KG)=         .02
    SCALE HEIGHT (KM)              =       30.00
    OTV MASS (KG)                  =     2270.00
    SOC MASS (KG)                  =   100000.00
    ANNUAL SOC CARGO MASS (KG/YR)  =    20000.00
    OTV SPECIFIC IMPULSE (SEC)     =      455.00
    SOC SPECIFIC IMPULSE (SEC)     =      455.00
    ORB SPECIFIC IMPULSE (SEC)     =      313.00

FUEL CONSUMPTION
---- -----------

    ORBITER FUEL MASS (KG/MSN)     =     8277.78
    SOC FUEL MASS (KG/YR)          =    35629.92
    OTV FUEL MASS (KG/YR)          =   571779.56
    TOTAL STS FUEL MASS (KG/YR)    =   992732.79

SOC LOCATION AND RESUPPLY PARAMETERS
--- -------- --- -------- ----------

    ORBIT INCLINATION (DEG)        =       57.00
    ORBIT RADIUS (KM)              =     6670.37
    NO OF ORB LAUNCHES (LS/YR)     =       46.35
    ORB PAYLOAD MASS (KG/MSN)      =    15175.57
```

Computer Run D-2 Run Number 10

```
     ETR MODEL II LAUNCH MINIMIZATION PROGRAM
     === ===== == ====== ============ =======


 SATELLITE TRAFFIC MODEL
 --------- ------- -----


     MISSION    ASAT    ESAT    ISAT   MSAT     FSAT    OTV FUEL
       (#)      (KM)           (DEG)   (KG)   (LS/YR)     (KG)

        1      41000.   0.00    0.0    2000.    3.00     20820.
        2      20000.   0.00    0.0     500.     .50     15542.
        3       6700.   0.00   28.5   25000.     .50       126.

 VARIABLE PARAMETERS
 -------- ----------

     BALLISTIC COEFFICIENT (M**2/KG)=        .02
     SCALE HEIGHT (KM)              =      30.00
     OTV MASS (KG)                  =    2270.00
     SOC MASS (KG)                  =  100000.00
     ANNUAL SOC CARGO MASS (KG/YR)  =   20000.00
     OTV SPECIFIC IMPULSE (SEC)     =     455.00
     SOC SPECIFIC IMPULSE (SEC)     =     455.00
     ORB SPECIFIC IMPULSE (SEC)     =     313.00

 FUEL CONSUMPTION
 ---- -----------

     ORBITER FUEL MASS (KG/MSN)     =   10278.08
     SOC FUEL MASS (KG/YR)          =    4669.75
     OTV FUEL MASS (KG/YR)          =   70294.70
     TOTAL STS FUEL MASS (KG/YR)    =  133549.18

 SOC LOCATION AND RESUPPLY PARAMETERS
 --- -------- --- -------- ----------

     ORBIT INCLINATION (DEG)        =      28.50
     ORBIT RADIUS (KM)              =    6729.44
     NO OF ORB LAUNCHES (LS/YR)     =       5.70
     ORB PAYLOAD MASS (KG/MSN)      =   19950.01
```

Computer Run D-3   Run Number 55

```
100=    ETR MODEL III LAUNCH MINIMIZATION PROGRAM
110=    === ===== === ====== ============ =======
120=
130=
140= SATELLITE TRAFFIC MODEL
150= --------- ------- -----
160=
170=
180=     MISSION    ASAT    ESAT    ISAT    MSAT     FSAT     OTV FUEL
190=       (#)      (KM)            (DEG)   (KG)    (LS/YR)    (KG)
200=
210=        1      41000.   0.00      0.0   2000.    3.00     31279.
220=        2      20000.   0.00      0.0    500.     .50     36417.
230=        3       6700.   0.00     28.5  25000.     .50     53733.
240=        4      65000.   0.00     55.0   1500.    4.00     18148.
250=        5      25000.    .70     65.0   1500.     .50      7851.
260=        6      12000.   0.00     90.0   4500.    3.00     24593.
270=        7       6700.   0.00     98.0   8000.    5.00     56177.
280=
290= VARIABLE PARAMETERS
300= -------- ----------
310=
320=     BALLISTIC COEFFICIENT (M**2/KG)=        .02
330=     SCALE HEIGHT (KM)              =      30.00
340=     OTV MASS (KG)                  =    2270.00
350=     SOC MASS (KG)                  =  100000.00
360=     ANNUAL SOC CARGO MASS (KG/YR)  =   20000.00
370=     OTV SPECIFIC IMPULSE (SEC)     =     455.00
380=     SOC SPECIFIC IMPULSE (SEC)     =     455.00
390=     ORB SPECIFIC IMPULSE (SEC)     =     313.00
400=
410= FUEL CONSUMPTION
420= ---- -----------
430=
440=     ORBITER FUEL MASS (KG/MSN)     =    4859.20
450=     SOC FUEL MASS (KG/YR)          =    4189.47
460=     OTV FUEL MASS (KG/YR)          =  595837.88
470=     TOTAL STS FUEL MASS (KG/YR)    =  782239.98
480=
490= SOC LOCATION AND RESUPPLY PARAMETERS
500= --- -------- --- -------- ----------
510=
520=     ORBIT INCLINATION (DEG)        =      57.00
530=     ORBIT RADIUS (KM)              =    6734.31
540=     NO OF ORB LAUNCHES (LS/YR)     =      37.50
550=     ORB PAYLOAD MASS (KG/MSN)      =   18641.47
560=     RENDEZVOUS INCLINATION (DEG)   =      56.84
570=     RENDEZVOUS RADIUS (KM)         =    6538.10
580=     PAYLOAD MASS TO SOC (KG)       =   18024.02
```

ETR MODEL III LAUNCH MINIMIZATION PROGRAM

SATELLITE TRAFFIC MODEL

MISSION (#)	ASAT (KM)	ESAT	ISAT (DEG)	MSAT (KG)	FSAT (LS/YR)	OTV FUEL (KG)
1	41000.	0.00	0.0	2000.	3.00	20443.
2	20000.	0.00	0.0	500.	.50	15229.
3	6700.	0.00	28.5	25000.	.50	550.

VARIABLE PARAMETERS

BALLISTIC COEFFICIENT (M**2/KG)	=	.02
SCALE HEIGHT (KM)	=	30.00
OTV MASS (KG)	=	2270.00
SOC MASS (KG)	=	100000.00
ANNUAL SOC CARGO MASS (KG/YR)	=	20000.00
OTV SPECIFIC IMPULSE (SEC)	=	455.00
SOC SPECIFIC IMPULSE (SEC)	=	455.00
ORB SPECIFIC IMPULSE (SEC)	=	313.00

FUEL CONSUMPTION

ORBITER FUEL MASS (KG/MSN)	=	4985.72
SOC FUEL MASS (KG/YR)	=	169.58
OTV FUEL MASS (KG/YR)	=	74806.78
TOTAL STS FUEL MASS (KG/YR)	=	97439.88

SOC LOCATION AND RESUPPLY PARAMETERS

ORBIT INCLINATION (DEG)	=	28.50
ORBIT RADIUS (KM)	=	6828.47
NO OF ORB LAUNCHES (LS/YR)	=	4.51
ORB PAYLOAD MASS (KG/MSN)	=	25242.37
RENDEZVOUS INCLINATION (DEG)	=	28.50
RENDEZVOUS RADIUS (KM)	=	6538.10
PAYLOAD MASS TO SOC (KG)	=	24100.54

Computer Run D-5 Table 4.15 Efficient Operating Point for ETR Scenario A, Missions 1-7, Level I Technology, Run Number 108

```
100=    ETR MODEL VI DUAL OBJECTIVE MINIMIZATION PROGRAM
110=    === ===== == ==== ========= =========== =======
120=
130= SATELLITE TRAFFIC MODEL
140= --------- ------- -----
150=MSN    ASAT   ESAT   ISAT   MSAT   FSAT    OTV    DEPLOY   RETURN
160=                                           FUEL    TIME     TIME
170= #      KM            DEG     KG    #/YR    KG     DAYS     DAYS
180=
190= 1   41000.  .000    0.0  2000.  2.25   6051.   125.7     76.5
200= 2   20000.  .000    0.0   500.   .38   5415.   105.9     75.0
210= 3    6700.  .000   28.5 25000.   .38   1559.    43.1      9.0
220= 4   65000.  .000   55.0  1500.  3.00   5171.   104.5     68.3
230= 5   25000.  .700   65.0  1500.   .38   5658.   115.1     73.9
240= 6   12000.  .000   90.0  4500.  2.25  11673.   268.9    121.2
250= 7    6700.  .000   98.0  8000.  3.75  18938.   471.6    161.3
260=
270= CONSTANT PARAMETERS
280= -------- ----------
290=     ION THRUSTER MASS (KG)            =     51.36
300=     THRUSTER FUEL TANK MASS (KG)      =     12.00
310=     SPECIFIC MASS (KG/KW)             =     10.00
320=     THRUSTER POWER (KW/THRUSTER)      =      3.06
330=     ION THRUSTER THRUST (MN)          =    129.00
340=     EXPENDED MASS AT ETS (KG)         =  38399.00
350=     SHUTTLE REFERENCE MASS (KG)       =  85000.00
360=     BALLISTIC COEFFICIENT (M**2/KG)=           .02
370=     SCALE HEIGHT (KM)                 =     30.00
380=     CHEMICAL OTV MASS (KG)            =   2270.00
390=     SOC MASS (KG)                     = 100000.00
400=     ANNUAL SOC CARGO MASS (KG/YR)     =  20000.00
410=     CHEMICAL OTV SPECIFIC IMPULSE     =    455.00
420=     ION OTV SPECIFIC IMPULSE (SEC)    =   2900.00
430=     SOC SPECIFIC IMPULSE (SEC)        =   2900.00
440=     ORB SPECIFIC IMPULSE (SEC)        =    313.00
450= FUEL CONSUMPTION
460= ---- -----------
470=     ORBITER FUEL MASS (KG/MSN)        =   4874.09
480=     SOC FUEL MASS (KG/YR)             =   7258.64
490=     OTV FUEL MASS (KG/YR)             = 136096.27
500=     TOTAL STS FUEL MASS (KG/YR)       = 183132.19
510= SOC LOCATION AND RESUPPLY PARAMETERS
520= --- -------- --- -------- ----------
530=     ORBIT INCLINATION (DEG)           =     33.12
540=     ORBIT RADIUS (KM)                 =   6661.22
550=     NUMBER OF OTV ION THRUSTERS (#)=         67.74
560=     NO OF ORB LAUNCHES (LS/YR)        =      8.16
570=     AVG OTV TIME OF FLIGHT (DAYS)     =    260.00
580=     ION OTV MASS (KG)                 =   6665.01
590=     NO OF ION PROPELLED OTV'S (#)     =      4.98
600=     ORB PAYLOAD MASS (KG/MSN)         =  27531.12
610=     PAYLOAD MASS TO SOC (KG)          =  26968.35
```

Computer Run D-6 Table 4.15 Efficient Operating Point for WTR Scenario A, Missions 1-7, Level I Technology, Run Number 107

```
100=     WTR MODEL VI DUAL OBJECTIVE MINIMIZATION PROGRAM
110=     === ===== == ==== ========= =========== =======
120=
130= SATELLITE TRAFFIC MODEL
140= --------- ------- -----
150=MSN    ASAT   ESAT   ISAT   MSAT   FSAT    OTV   DEPLOY   RETURN
160=                                           FUEL   TIME     TIME
170= #      KM           DEG     KG    #/YR    KG     DAYS     DAYS
180=
190= 1   41000.  .000    0.0  2000.  2.25   7451.   189.7    104.4
200= 2   20000.  .000    0.0   500.   .38   7610.   184.9    115.4
210= 3    6700.  .000   28.5 25000.   .38  11088.   372.2     65.5
220= 4   65000.  .000   55.0  1500.  3.00   3477.    82.5     54.7
230= 5   25000.  .700   65.0  1500.   .38   2641.    61.7     42.5
240= 6   12000.  .000   90.0  4500.  2.25   5500.   147.1     70.0
250= 7    6700.  .000   98.0  8000.  3.75   8349.   242.6     86.9
260=
270= CONSTANT PARAMETERS
280= -------- ----------
290=     ION THRUSTER MASS (KG)             =      51.36
300=     THRUSTER FUEL TANK MASS (KG)       =      12.00
310=     SPECIFIC MASS (KG/KW)              =      10.00
320=     THRUSTER POWER (KW/THRUSTER)       =       3.06
330=     ION THRUSTER THRUST (MN)           =     129.00
340=     EXPENDED MASS AT ETS (KG)          =   38399.00
350=     SHUTTLE REFERENCE MASS (KG)        =   85000.00
360=     BALLISTIC COEFFICIENT (M**2/KG)    =        .02
370=     SCALE HEIGHT (KM)                  =      30.00
380=     CHEMICAL OTV MASS (KG)             =    2270.00
390=     SOC MASS (KG)                      =  100000.00
400=     ANNUAL SOC CARGO MASS (KG/YR)      =   20000.00
410=     CHEMICAL OTV SPECIFIC IMPULSE      =     435.00
420=     ION OTV SPECIFIC IMPULSE (SEC)     =    2900.00
430=     SOC SPECIFIC IMPULSE (SEC)         =    2900.00
440=     ORB SPECIFIC IMPULSE (SEC)         =     313.00
450= FUEL CONSUMPTION
460= ---- -----------
470=     ORBITER FUEL MASS (KG/MSN)         =    8255.52
480=     SOC FUEL MASS (KG/YR)              =    1588.41
490=     OTV FUEL MASS (KG/YR)              =   83950.63
500=     TOTAL STS FUEL MASS (KG/YR)        =  153014.12
510= SOC LOCATION AND RESUPPLY PARAMETERS
520= --- -------- --- -------- ----------
530=     ORBIT INCLINATION (DEG)            =      59.00
540=     ORBIT RADIUS (KM)                  =    6708.07
550=     NUMBER OF OTV ION THRUSTERS (#)    =      57.36
560=     NO OF ORB LAUNCHES (LS/YR)         =       8.17
570=     AVG OTV TIME OF FLIGHT (DAYS)      =     260.00
580=     ION OTV MASS (KG)                  =    5689.28
590=     NO OF ION PROPELLED OTV'S (#)      =       4.98
600=     ORB PAYLOAD MASS (KG/MSN)          =   20378.57
610=     PAYLOAD MASS TO SOC (KG)           =   19816.11
```

Computer Run D-7 Table 4.15 Efficient Operating Point for ETR Scenario B, Missions 1-3, Level I Technology, Run Number 109

```
100=    ETR MODEL VI DUAL OBJECTIVE MINIMIZATION PROGRAM
110=    === ===== == ==== ========= =========== =======
120=
130= SATELLITE TRAFFIC MODEL
140= --------- ------- -----
150=MSN    ASAT   ESAT   ISAT   MSAT   FSAT    OTV    DEPLOY   RETURN
160=                                           FUEL    TIME     TIME
170= #      KM            DEG     KG    #/YR    KG     DAYS     DAYS
180=
190= 1   41000.  .000    0.0  2000.  2.25   4638.   121.7     72.0
200= 2   20000.  .000    0.0   500.   .38   3934.    95.8     68.6
210= 3    6700.  .000   28.5 25000.   .38     46.     1.6       .3
220=
230= CONSTANT PARAMETERS
240= -------- ----------
250=      ION THRUSTER MASS (KG)               =      51.36
260=      THRUSTER FUEL TANK MASS (KG)         =      12.00
270=      SPECIFIC MASS (KG/KW)                =      10.00
280=      THRUSTER POWER (KW/THRUSTER)         =       3.06
290=      ION THRUSTER THRUST (MN)             =     129.00
300=      EXPENDED MASS AT ETS (KG)            =   38399.00
310=      SHUTTLE REFERENCE MASS (KG)          =   85000.00
320=      BALLISTIC COEFFICIENT (M**2/KG)=              .02
330=      SCALE HEIGHT (KM)                    =      30.00
340=      CHEMICAL OTV MASS (KG)               =    2270.00
350=      SOC MASS (KG)                        =  100000.00
360=      ANNUAL SOC CARGO MASS (KG/YR)        =   20000.00
370=      CHEMICAL OTV SPECIFIC IMPULSE        =     455.00
380=      ION OTV SPECIFIC IMPULSE (SEC)       =    2900.00
390=      SOC SPECIFIC IMPULSE (SEC)           =    2900.00
400=      ORB SPECIFIC IMPULSE (SEC)           =     313.00
410= FUEL CONSUMPTION
420= ---- -----------
430=      ORBITER FUEL MASS (KG/MSN)           =    4890.33
440=      SOC FUEL MASS (KG/YR)                =     293.96
450=      OTV FUEL MASS (KG/YR)                =   14122.87
460=      TOTAL STS FUEL MASS (KG/YR)          =   22828.21
470= SOC LOCATION AND RESUPPLY PARAMETERS
480= --- -------- --- -------- ----------
490=      ORBIT INCLINATION (DEG)              =      28.50
500=      ORBIT RADIUS (KM)                    =    6756.71
510=      NUMBER OF OTV ION THRUSTERS (#)=             54.19
520=      NO OF ORB LAUNCHES (LS/YR)           =       1.72
530=      AVG OTV TIME OF FLIGHT (DAYS)        =     120.00
540=      ION OTV MASS (KG)                    =    5392.16
550=      NO OF ION PROPELLED OTV'S (#)        =        .99
560=      ORB PAYLOAD MASS (KG/MSN)            =   28378.75
570=      PAYLOAD MASS TO SOC (KG)             =   27194.41
```

Computer Run D-8 Table 4.15 Efficient Operating Point for ETR Scenario B, Missions 4-7, Level I Technology, Run Number 112

```
100=    ETR MODEL VI DUAL OBJECTIVE MINIMIZATION PROGRAM
110=    === ===== == ==== ========= =========== =======
120=
130= SATELLITE TRAFFIC MODEL
140= --------- ------- -----
150=MSN   ASAT   ESAT   ISAT   MSAT   FSAT    OTV    DEPLOY   RETURN
160=                                          FUEL    TIME     TIME
170= #     KM           DEG     KG    #/YR     KG     DAYS     DAYS
180=
190= 4   65000.  .000   55.0   1500.  3.00   2842.    83.7     53.8
200= 5   25000.  .700   65.0   1500.   .38   2357.    68.7     45.3
210= 6   12000.  .000   90.0   4500.  2.25   5058.   170.2     74.5
220= 7    6700.  .000   98.0   8000.  3.75   7938.   290.6     93.3
230=
240= CONSTANT PARAMETERS
250= -------- ----------
260=     ION THRUSTER MASS (KG)             =     51.36
270=     THRUSTER FUEL TANK MASS (KG)       =     12.00
280=     SPECIFIC MASS (KG/KW)              =     10.00
290=     THRUSTER POWER (KW/THRUSTER)       =      3.06
300=     ION THRUSTER THRUST (MN)           =    129.00
310=     EXPENDED MASS AT ETS (KG)          =  38399.00
320=     SHUTTLE REFERENCE MASS (KG)        =  85000.00
330=     BALLISTIC COEFFICIENT (M**2/KG)    =       .02
340=     SCALE HEIGHT (KM)                  =     30.00
350=     CHEMICAL OTV MASS (KG)             =   2270.00
360=     SOC MASS (KG)                      = 100000.00
370=     ANNUAL SOC CARGO MASS (KG/YR)      =  20000.00
380=     CHEMICAL OTV SPECIFIC IMPULSE      =    455.00
390=     ION OTV SPECIFIC IMPULSE (SEC)     =   2900.00
400=     SOC SPECIFIC IMPULSE (SEC)         =   2900.00
410=     ORB SPECIFIC IMPULSE (SEC)         =    313.00
420= FUEL CONSUMPTION
430= ---- -----------
440=     ORBITER FUEL MASS (KG/MSN)         =   4762.92
450=     SOC FUEL MASS (KG/YR)              =    995.30
460=     OTV FUEL MASS (KG/YR)              =  54462.15
470=     TOTAL STS FUEL MASS (KG/YR)        =  82054.50
480= SOC LOCATION AND RESUPPLY PARAMETERS
490= --- -------- --- -------- ----------
500=     ORBIT INCLINATION (DEG)            =     57.00
510=     ORBIT RADIUS (KM)                  =   6721.92
520=     NUMBER OF OTV ION THRUSTERS (#)    =     46.80
530=     NO OF ORB LAUNCHES (LS/YR)         =      5.58
540=     AVG OTV TIME OF FLIGHT (DAYS)      =    220.00
550=     ION OTV MASS (KG)                  =   4697.76
560=     NO OF ION PROPELLED OTV'S (#)      =      2.41
570=     ORB PAYLOAD MASS (KG/MSN)          =  21731.42
580=     PAYLOAD MASS TO SOC (KG)           =  21094.33
```

Computer Run D-9 Table 4.15 Efficient Operating Point for WTR Scenario B, Missions 4-7, Level I Technology, Run Number 113

```
100=    WTR MODEL VI DUAL OBJECTIVE MINIMIZATION PROGRAM
110=    === ===== == ==== ========= =========== =======
120=
130= SATELLITE TRAFFIC MODEL
140= --------- ------- -----
150=MSN   ASAT   ESAT   ISAT   MSAT   FSAT    OTV    DEPLOY   RETURN
160=                                          FUEL    TIME     TIME
170= #     KM           DEG     KG    #/YR    KG     DAYS     DAYS
180=
190= 4   65000.  .000   55.0  1500.  3.00    2190.    99.4     58.2
200= 5   25000.  .700   65.0  1500.   .38    1592.    71.3     43.3
210= 6   12000.  .000   90.0  4500.  2.25    3650.   191.4     71.3
220= 7    6700.  .000   98.0  8000.  3.75    5907.   337.1     88.0
230=
240= CONSTANT PARAMETERS
250= -------- ----------
260=     ION THRUSTER MASS (KG)               =     51.36
270=     THRUSTER FUEL TANK MASS (KG)         =     12.00
280=     SPECIFIC MASS (KG/KW)                =     10.00
290=     THRUSTER POWER (KW/THRUSTER)         =      3.06
300=     ION THRUSTER THRUST (MN)             =    129.00
310=     EXPENDED MASS AT ETS (KG)            =  38399.00
320=     SHUTTLE REFERENCE MASS (KG)          =  85000.00
330=     BALLISTIC COEFFICIENT (M**2/KG)      =       .02
340=     SCALE HEIGHT (KM)                    =     30.00
350=     CHEMICAL OTV MASS (KG)               =   2270.00
360=     SOC MASS (KG)                        = 100000.00
370=     ANNUAL SOC CARGO MASS (KG/YR)        =  20000.00
380=     CHEMICAL OTV SPECIFIC IMPULSE        =    455.00
390=     ION OTV SPECIFIC IMPULSE (SEC)       =   2900.00
400=     SOC SPECIFIC IMPULSE (SEC)           =   2900.00
410=     ORB SPECIFIC IMPULSE (SEC)           =    313.00
420= FUEL CONSUMPTION
430= ---- -----------
440=     ORBITER FUEL MASS (KG/MSN)           =   8239.82
450=     SOC FUEL MASS (KG/YR)                =   5648.36
460=     OTV FUEL MASS (KG/YR)                =  40213.27
470=     TOTAL STS FUEL MASS (KG/YR)          =  91660.95
480= SOC LOCATION AND RESUPPLY PARAMETERS
490= --- -------- --- -------- ----------
500=     ORBIT INCLINATION (DEG)              =     60.06
510=     ORBIT RADIUS (KM)                    =   6670.23
520=     NUMBER OF OTV ION THRUSTERS (#)      =     31.43
530=     NO OF ORB LAUNCHES (LS/YR)           =      5.56
540=     AVG OTV TIME OF FLIGHT (DAYS)        =    240.00
550=     ION OTV MASS (KG)                    =   3255.46
560=     NO OF ION PROPELLANT OTV'S (#)       =      2.63
570=     ORB PAYLOAD MASS (KG/MSN)            =  20075.22
580=     PAYLOAD MASS TO SOC (KG)             =  19638.13
```

Computer Run D-10 Table 4.15 Efficient Operating Point for ETR Scenario A, Missions 1-7, Level II Technology, Run Number 110

```
100=    ETR MODEL VI DUAL OBJECTIVE MINIMIZATION PROGRAM
110=    === ===== == ==== ========= =========== =======
120=
130= SATELLITE TRAFFIC MODEL
140= --------- ------- -----
150=MSN    ASAT   ESAT   ISAT   MSAT   FSAT    OTV    DEPLOY   RETURN
160=                                           FUEL    TIME     TIME
170= #      KM           DEG     KG    #/YR     KG     DAYS     DAYS
180=
190= 1   41000.  .000    0.0  2000.  2.25    3653.    61.9     35.7
200= 2   20000.  .000    0.0   500.   .38    3263.    51.0     36.2
210= 3    6700.  .000   28.5 25000.   .38    2922.    67.8     10.3
220= 4   65000.  .000   55.0  1500.  3.00    2629.    42.8     27.5
230= 5   25000.  .700   65.0  1500.   .38    2756.    44.9     28.7
240= 6   12000.  .000   90.0  4500.  2.25    5934.   111.6     47.0
250= 7    6700.  .000   98.0  8000.  3.75   10272.   210.4     64.1
260=
270= CONSTANT PARAMETERS
280= -------- ----------
290=      ION THRUSTER MASS (KG)                =     51.36
300=      THRUSTER FUEL TANK MASS (KG)          =     12.00
310=      SPECIFIC MASS (KG/KW)                 =      5.00
320=      THRUSTER POWER (KW/THRUSTER)          =      6.86
330=      ION THRUSTER THRUST (MN)              =    298.00
340=      EXPENDED MASS AT ETS (KG)             =  38399.00
350=      SHUTTLE REFERENCE MASS (KG)           =  85000.00
360=      BALLISTIC COEFFICIENT (M**2/KG)=              .02
370=      SCALE HEIGHT (KM)                     =     30.00
380=      CHEMICAL OTV MASS (KG)                =   2270.00
390=      SOC MASS (KG)                         = 100000.00
400=      ANNUAL SOC CARGO MASS (KG/YR)         =  20000.00
410=      CHEMICAL OTV SPECIFIC IMPULSE         =    455.00
420=      ION OTV SPECIFIC IMPULSE (SEC)        =   3448.00
430=      SOC SPECIFIC IMPULSE (SEC)            =   2900.00
440=      ORB SPECIFIC IMPULSE (SEC)            =    313.00
450= FUEL CONSUMPTION
460= ---- -----------
470=      ORBITER FUEL MASS (KG/MSN)            =   4850.57
480=      SOC FUEL MASS (KG/YR)                 =       .00
490=      OTV FUEL MASS (KG/YR)                 =  85966.65
500=      TOTAL STS FUEL MASS (KG/YR)           = 116554.06
510= SOC LOCATION AND RESUPPLY PARAMETERS
520= --- -------- --- -------- ----------
530=      ORBIT INCLINATION (DEG)               =     39.02
540=      ORBIT RADIUS (KM)                     =   7087.77
550=      NUMBER OF OTV ION THRUSTERS (#)=            43.59
560=      NO OF ORB LAUNCHES (LS/YR)            =      6.31
570=      AVG OTV TIME OF FLIGHT (DAYS)         =    120.00
580=      ION OTV MASS (KG)                     =   4557.63
590=      NO OF ION PROPELLED OTV'S (#)         =      2.30
600=      ORB PAYLOAD MASS (KG/MSN)             =  26304.03
610=      PAYLOAD MASS TO SOC (KG)              =  24166.57
```

Computer Run D-11 Table 4.15 Efficient Operating Point for ETR Scenario A, Missions 1-7, Level III Technology, Run Number 111

```
100=    ETR MODEL VI DUAL OBJECTIVE MINIMIZATION PROGRAM
110=    === ===== == ==== ========= =========== =======
120=
130= SATELLITE TRAFFIC MODEL
140= --------- ------- -----
150=MSN    ASAT   ESAT   ISAT   MSAT   FSAT    OTV   DEPLOY  RETURN
160=                                           FUEL   TIME    TIME
170= #      KM           DEG     KG    #/YR    KG     DAYS    DAYS
180=
190= 1   41000.  .000    0.0  2000.  2.25   2549.    20.6    12.9
200= 2   20000.  .000    0.0   500.   .38   2315.    17.2    13.2
210= 3    6700.  .000   28.5 25000.   .38   2527.    28.5     4.7
220= 4   65000.  .000   55.0  1500.  3.00   1768.    13.7     9.5
230= 5   25000.  .700   65.0  1500.   .38   1823.    14.2     9.8
240= 6   12000.  .000   90.0  4500.  2.25   3785.    33.9    15.9
250= 7    6700.  .000   98.0  8000.  3.75   6520.    63.9    21.9
260=
270= CONSTANT PARAMETERS
280= -------- ----------
290=     ION THRUSTER MASS (KG)               =     40.00
300=     THRUSTER FUEL TANK MASS (KG)         =     12.00
310=     SPECIFIC MASS (KG/KW)                =      1.00
320=     THRUSTER POWER (KW/THRUSTER)         =     10.00
330=     ION THRUSTER THRUST (MN)             =    500.00
340=     EXPENDED MASS AT ETS (KG)            =  38399.00
350=     SHUTTLE REFERENCE MASS (KG)          =  80000.00
360=     BALLISTIC COEFFICIENT (M**2/KG)=           .02
370=     SCALE HEIGHT (KM)                    =     30.00
380=     CHEMICAL OTV MASS (KG)               =   2270.00
390=     SOC MASS (KG)                        = 200000.00
400=     ANNUAL SOC CARGO MASS (KG/YR)        =  26250.00
410=     CHEMICAL OTV SPECIFIC IMPULSE        =    455.00
420=     ION OTV SPECIFIC IMPULSE (SEC)       =   5000.00
430=     SOC SPECIFIC IMPULSE (SEC)           =   2900.00
440=     ORB SPECIFIC IMPULSE (SEC)           =    313.00
450= FUEL CONSUMPTION
460= ---- -----------
470=     ORBITER FUEL MASS (KG/MSN)           =   4685.21
480=     SOC FUEL MASS (KG/YR)                =       .00
490=     OTV FUEL MASS (KG/YR)                =  65068.40
500=     TOTAL STS FUEL MASS (KG/YR)          =  87849.65
510= SOC LOCATION AND RESUPPLY PARAMETERS
520= --- -------- --- -------- ----------
530=     ORBIT INCLINATION (DEG)              =     41.00
540=     ORBIT RADIUS (KM)                    =   7356.41
550=     NUMBER OF OTV ION THRUSTERS (#)=            76.56
560=     NO OF ORB LAUNCHES (LS/YR)           =      4.86
570=     AVG OTV TIME OF FLIGHT (DAYS)        =     40.00
580=     ION OTV MASS (KG)                    =   5046.57
590=     NO OF ION PROPELLED OTV'S (#)        =       .77
600=     ORB PAYLOAD MASS (KG/MSN)            =  31015.72
610=     PAYLOAD MASS TO SOC (KG)             =  27469.14
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Vita

Jess M. Sponable was [redacted] His family returned to the United States shortly thereafter and settled in Roseville California. He graduated [redacted] in 1974 and was appointed as a cadet to the United States Air Force Academy. In 1978 Sponable graduated from the Academy with a B.S. in physics and was commissioned in the Air Force. His first assignment was to Vandenberg AFB, California where he worked launch operations for the Global Positioning System satellites. He also attended night classes to obtain a M.S. in Systems Management from the University of Southern California. Arriving at the Air Force Institute of Technology in 1981 Sponable began graduate class work to obtain a M.S. in Astronautical Engineering. His next assignment is to Space Division/YOM at Los Angelos AFS beginning in January 1983. [redacted]

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Space station	Optimization	Space Tug
Orbital Transfer Vehicle	Hohmann Transfer	Satellite
Space Transportation System	Ion propulsion	Testing
Nonlinear programming	Satellite Traffic Model	Satellite Servicing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study examines a scenario for bolstering the operational control exercised over the U.S. satellite fleet. An Extended Space Transportation System (STS) composed of a Shuttle, Space Station, and Orbital Transfer Vehicle (OTV) is analysed using a nonlinear optimization technique. The OTV deploys a postulated fleet of military satellites across the entire gamut of inclinations and altitudes. The total Station, OTV, Shuttle propellant and Shuttle payload mass required in orbit are calculated as a function of inclination and altitude, and used to minimize annual Shuttle launches. Launch rates

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